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ONR/MARCORSYSCOM EVALUATION OF SELF-APPLIED TOURNIQUETS FOR COMBAT APPLICATIONS

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19. ABSTRACT

Six tourniquets designed for combat application were tested for their ease of use and ability to occlude arterial blood flow to the upper arms and thighs in a repeated measures design. To simulate nighttime desert combat conditions, subjects completed an exercise routine while the tourniquet was immersed in a blood analog solution and rolled in sand. Subjects then applied the tourniquet while they were blindfolded and seated or lying supine. They were able to apply all tourniquets in a reasonable amount of time (range: 24-204 s). The Quickette exhibited a high mechanical failure rate (30%). All tourniquets except the One-Handed Tourniquet (1-inch width) and Quickette performed reasonably well on arms and legs, with median occlusion efficacies exceeding 70%. Subjective rankings indicated that the Mechanical Advantage Tourniquet, Tourni-Kwik, and Combat Application Tourniquet were preferred over the One-Handed Tourniquet (1- and 2-inch models) and the Quickette. Additional research is recommended to investigate increases in blood flow that might occur with inadequate tourniquet application.

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INTRODUCTION

Mortality statistics updated from Operation Iraqi Freedom (OIF), 19 March – 30 November 2004 indicate that death to U.S. forces is often not immediate but rather from hemorrhagic shock following the detonation of an improvised explosive device (IED). U.S. troops are currently being equipped with body armor and Kevlar helmets that have decreased the number of fatalities resulting from penetrating chest wounds and serious head trauma, but increased the number of deaths attributable to extremity wounds.[1] Evidence suggests that about 7% of these deaths could be prevented with the prompt application of an effective tourniquet.[2,3] A lightweight self-carried tourniquet that can be either self-applied or applied by other non-medical personnel in the field has not been identified.

Many candidate tourniquets have been tested over the past several years using a wide range of objectives and methods. Although nearly all medical experts agree that the primary objective of any tourniquet device is to achieve hemostasis, no methodological gold standard exists for assessing arterial occlusion distal to tourniquet placement. One evaluation of possible tourniquets for combat established the criteria that a tourniquet must occlude detectable (Doppler) blood flow in at least 75% of the subjects in order for the device to be considered successful.[4] The U.S. Army Institute of Surgical Research, Fort Sam Houston, conducted a physiological assessment of the Army one-handed tourniquet (OHT) that included the use of occlusion plethsmography, a method more sensitive than Doppler for determining blood flow. Their study demonstrated that a minimum of about 20% of baseline blood flow can be present in the absence of Doppler sound. The researchers concluded that Doppler auscultation may overestimate the effectiveness of a clinical procedure (e.g., a tourniquet) designed to occlude blood flow and may underestimate the actual amount of blood flow present.[5]

Their study also concluded that while the Army OHT is a welcome "first step" that can effectively minimize blood flow in the arm, it does not work in the lower extremities. This conclusion is particularly disturbing, since the majority of battlefield wounds requiring tourniquet application occur in the lower limbs.[6] The Army report attributed the OHT's inability to stop leg blood flow effectively to its relatively narrow one-inch width. Previous investigators have clearly demonstrated an inverse relationship between tourniquet minimum width and the minimum pressure required to occlude arterial blood flow: i.e., as the width of a tourniquet decreases, the pressure required to occlude arterial blood flow increases exponentially.[7–9]

One aspect of tourniquet testing which has been lacking in the literature is that of a simulated "field test." For this study, subjects were asked to complete a rigorous period of pretrial exercise before tourniquets were applied. In addition to being fatigued and sweaty, subjects were then asked to apply a tourniquet that had been soaked in a blood analog solution and rolled in sand to determine the tourniquet's durability and ability to occlude blood flow when the site of administration was soaked with a slippery substance like blood. Other important measures tested were the percentage of arterial occlusion via impedance plethysmography (IPG)[10], tourniquet application times, the subject's ability to apply a tourniquet device during night simulation (blindfolded), and a human factors evaluation to determine its ease of use. The Office of Naval Research

(ONR)* funded a Marine Corps Systems Command (MarCorSysCom) objective for Navy Experimental Diving Unit (NEDU) to field test the five candidate tourniquets listed in Table 1 by product names, corresponding acronyms used in this study, and manufacturers. The tourniquets, which are illustrated in Figure 1, were tested for their application time and their ability to occlude blood flow in the forearms and legs.

Table 1.
Product Names, Acronyms, and Manufacturers of Tested Tourniquets

Product Name	Acronym	Manufacturer
Combat Application Tourniquet[11]	CAT	North American Rescue Products; Greenville, SC
Mechanical Advantage Tourniquet[12]	MAT	Bound Tree Medical; Henniker, NH
One-Hand Tourniquet		
1" width (U.S. Army, NSN 6515-01-504-0827)	OHT1	Canvass Specialties, Inc.; San Antonio, TX
2" width	OHT2	
Tourni-Kwik[13]	TK	H & H Associates; Bena, VA
Quickette	QUICK	Ivy Off; Laxahatchee, FL

* Due to the urgency of this tasking, the tourniquet protocol (NEDU Protocol 05-15/32169) was based upon criteria that ONR identified via email. Official NAVSEA *Task Assignment 05-07: Evaluation of Littoral Tourniquets*, was received 11 August 2005.

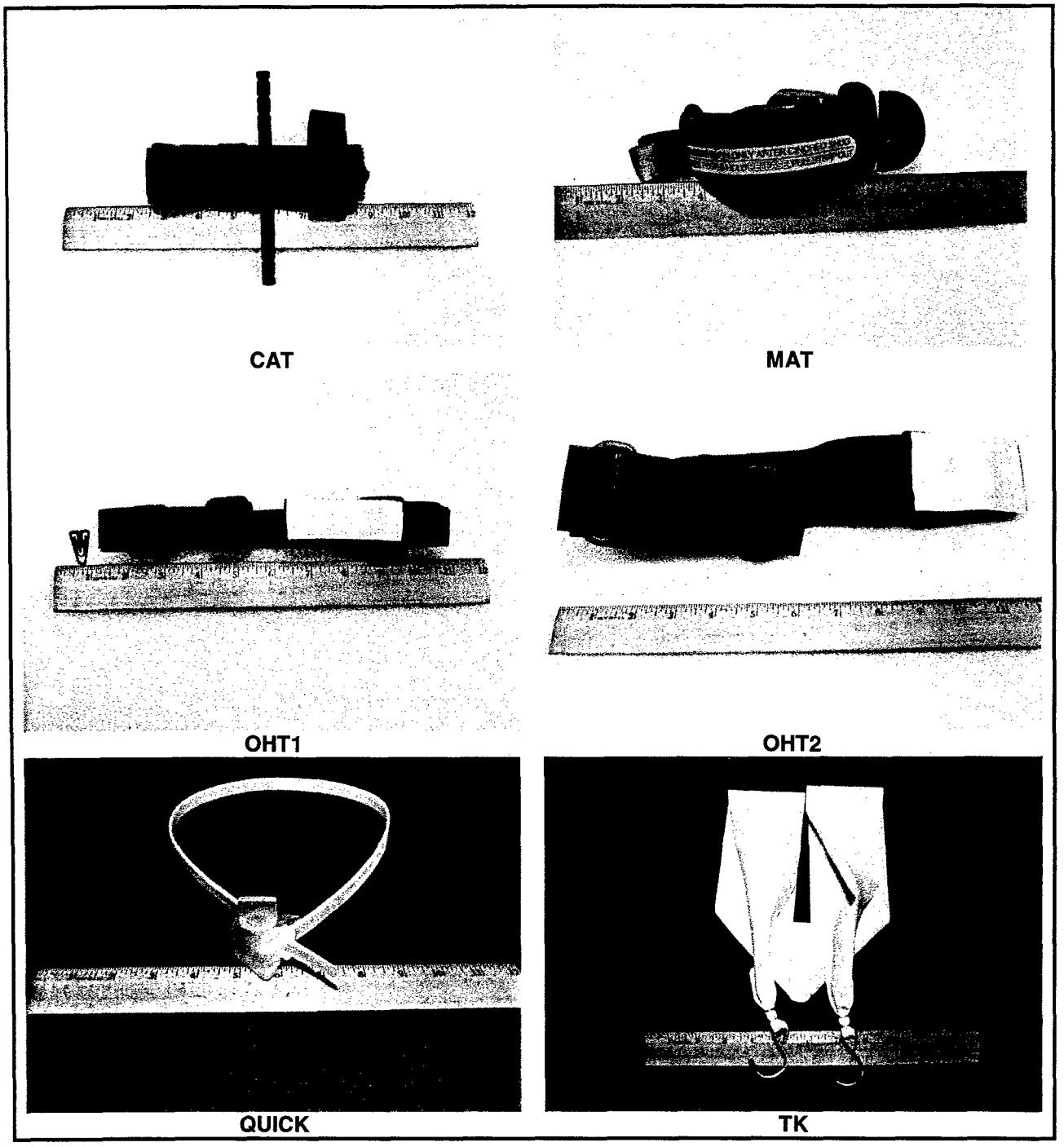

Figure 1. Tourniquets tested in the present work.

METHODS

GENERAL

Before any trials were undertaken, the NEDU Institutional Review Board reviewed and approved NEDU Protocol 05-15/32169, a detailed protocol prepared to provide background and detailed procedures for this work. Ten active duty Navy personnel served as test subjects, with appropriate informed consent being provided.

All combinations of tourniquet and extremity were tested in a repeated measures design. Subjects applied the tourniquets over long-sleeved battle dress uniforms (BDUs) worn in each trial. Before each tourniquet application, subjects completed 20 eight-count body builders[14] while the tourniquets were immersed in a blood analog solution and then rolled in sand to simulate desert combat (field) conditions.

EXPERIMENTAL DESIGN AND METHODS

Tourniquets were applied to four extremities:

- Upper right arm, approximately two inches above the right elbow
- Upper left arm, approximately two inches above the left elbow
- Lower right leg, approximately two inches above the right knee
- Lower left leg, approximately two inches above the left knee

During upper extremity trials, tourniquets were applied with the opposite hand: i.e., left hands were used to apply tourniquets to upper right arms, and right hands were used to apply tourniquets to upper left arms. Subjects were permitted to use both hands when applying tourniquets to the lower extremities. Hand dominance, defined as the hand used for writing, was recorded.

An example of a test matrix is shown in Table 2. Subjects occluded a given extremity only once on each test day, and a different test matrix was used for each subject to minimize potential order effects.

Table 2.
Example Test Matrix

Day	Extremity			
	Right Arm	Left Arm	Right Leg	Left Leg
1	CAT	MAT	OHT	QUICK
2	TK	CAT	MAT	OHT
3	QUICK	TK	CAT	MAT
4	OHT	QUICK	TK	CAT
5	MAT	OHT	QUICK	TK

Tourniquet efficacy was assessed with measured application time, presence or absence of arterial blood flow measured with an ultrasonic Doppler stethoscope (MedSonics #FP3A), and percentage of arterial occlusion measured with tetrapolar electrical IPG. IPG waveforms were measured with a THRIM Model #2992D (UFI; Morro Bay, CA), and recorded in real time for later analysis with electrocardiograms (EKGs) that were simultaneously acquired with a UFI Model 2121 Ambulatory ECG Bioamplifier (UFI; Morro Bay, CA). 3M™ Red Dot™ 2237 Monitoring Electrodes (3M; St. Paul, MN) were used for both the IPG and EKG applications. Electrode placement for IPG measurements on the two right extremities is illustrated in Figure 2. Electrocardiograms were acquired with electrodes positioned in Einthoven's triangle. Doppler stethoscope probe placement for monitoring each extremity was marked on each subject at the beginning of each test day.

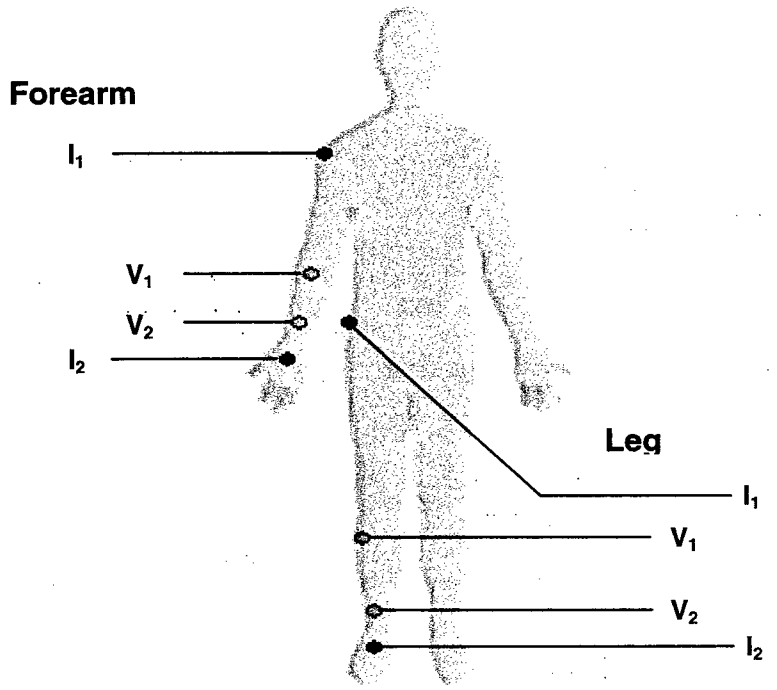

Figure 2. Electrode placements for IPG measurements on right extremities. On each extremity, the voltage developed in response to a current (0.8 mA, 50 kHz) passed between electrodes I_1 and I_2 was passively measured across electrodes V_1 and V_2. A separate set of electrodes (not shown) was similarly placed for monitoring the contralateral extremities.

IPG, EKG, and Doppler analog signals for the monitored extremity were passed through a DI-706 Interface (DATAQ Instruments; Akron, Ohio) to a DI-720 Analog-to-Digital converter (DATAQ Instruments; Akron, Ohio), where they were digitized at a sampling rate of 250 Hz per channel for recording with WinDaq/Professional Waveform Recording Software (DATAQ Instruments; Akron, Ohio) on a laptop personal computer. After each test, limb blood flows were determined from the recorded IPG waveforms with a custom program, Rheoencephalographic Impedance Scanning System (RheoSys), developed by LDM Associates (see Appendix A).

Calkins et al.[4] provided some guidance on parameter estimates for differences in tourniquet application time. The program was designed to detect a 5% difference in the percentage of circulatory occlusion and a 10 s difference in tourniquet application time in paired comparisons, each at 95% confidence and 80% power. With assumed standard deviations of 5% and 10 s, respectively, the required sample size was 10.

PROCEDURES

Training

NEDU medical department personnel briefed test subjects on the proper use of each tourniquet per the manufacturer's instructions. Following each brief, subjects practiced applying the tourniquet to the target extremities. After medical personnel verified that the tourniquet had been correctly applied in each practice application, the tourniquet was removed and all questions were addressed.

Pretest Tourniquet Preparation

A new tourniquet was used for each trial. Immediately before a tourniquet was handed to a subject for test, it was removed from its packaging, fully immersed in a blood analog solution, and then removed from the solution and rolled in beach sand.

The blood analog solution consisted of a mixture of five parts water with three parts Dowfrost® propylene glycol antifreeze concentrate (Hubbard-Hall Inc.; Waterbury, CT). The final mixture had a viscosity of about 3.2 centipoise at room temperature, approximately equal to that of whole blood at a physiological hematocrit of 45.[15-17]

Pretest Exercise and Tourniquet Application

Each subject was fitted with IPG and EKG electrodes at the beginning of each test day. Electrode sites were wiped with alcohol and allowed to dry before electrode application, but the sites were not abraded. Tourniquets were applied over long-sleeved BDUs worn by each subject throughout the trials.

Each trial proceeded as follows: Immediately after completing 20 eight-count body builders,[14] the subject assumed a supine position on the floor for testing and was blindfolded while electrode cables were threaded under the BDU and connected to the monitoring electrodes. The subject was then asked to remain still during the ensuing period, while baseline data was taken. At the end of this period, a technician handed the subject the test tourniquet prepared with sand-impregnated blood analog solution. This event, indicated in the record by a single event mark, marked the beginning of the application time period. While remaining supine or after assuming a seated position on the floor, the subject immediately began applying the tourniquet to the selected extremity (upper arm or thigh).

Applications to arms were performed one-handed, but use of both hands was allowed for applications to thighs. A maximum of 5 min was allowed to apply the tourniquet, after

which time the trial was terminated as an "application failure." Successful application occurred if the subject vocally declared, "Tourniquet on" — indicating that he had reached a point just before continued tightening would produce unbearable pain — within 5 min of being handed the test tourniquet. Upon such declaration, a double event mark was recorded to mark the end of the application time period. The subject was asked to remain still throughout the remainder of the procedure.

As soon as possible following tourniquet application, a technician positioned the Doppler probe and made a "Flow" or "No-flow" call based on the auditory output from the Doppler stethoscope. IPG measurements were continued, with the tourniquet applied for a period limited to a maximum of 30 s. The technician then released and removed the tourniquet, a triplet of event marks was entered into the record to mark the time of tourniquet release, and final sets of Doppler and IPG measurements were completed to confirm that circulation was restored. While resting for 10 min, the subject then dictated any comments about the tourniquet into a handheld tape recorder. The subject repeated this sequence on each of his remaining extremities.

Data Analysis

Three segments from the overall IPG record for each trial were extracted into separate WinDaq[18] files for analysis. Exact locations of these segments in different trials varied slightly depending upon the quality of the recorded data, but were extracted according to the following rules:

START = Pulse sequence nearest the end of the baseline period.

END = Pulse sequence after the subject had declared that the tourniquet was fully applied, and before the tourniquet was released.

POST = Pulse sequence after the tourniquet was released near the end of the test run.

The appropriate "START," "END," or "POST" designation was included in the filename of the extracted WinDaq file, and in the various tabulated data sheets, to denote the analyzed segment of the test. Data from the segments for each trial were analyzed as described in Appendix A.

Tape-recorded subject narratives taken after each trial were transcribed and are included in Appendix C.

TERMINATION CRITERIA

A test trial was terminated under any of the following circumstances:

- At the request of the test subject
- At the request of the Medical Supervisor
- At the request of the Principal Investigator
- If the tourniquet application was not completed within five (5) minutes

RESULTS

GENERAL

Forty applications of each tourniquet except the OHT models were tested, for a total of 200 trials. We had originally planned to run a complete set of trials to test the OHT2, as directed by our MARCORSYSCOM sponsor. However, the manufacturer forwarded only OHT1 tourniquets in response to our initial order. We immediately reported the error to the manufacturer, but we did not receive the proper OHT2 tourniquets until after testing had begun. As a result, the OHT test trials were split disproportionately between the OHT1 and OHT2 units. This situation therefore produced a substantially reduced dataset for subject × OHT × extremity combinations.

MECHANICAL AND APPLICATION FAILURES

Mechanical failures occurred in 16 trials. In the remaining trials, only one subject was unable to apply a tourniquet within 5 min. The number of applications and failures for each tourniquet are presented in Table 3, where results clearly indicate that all tourniquets except the QUICK were resistant to mechanical failure. The nature of each mechanical failure is described in Appendix B, and application times are listed in Appendix D.

Table 3.
Number of Tourniquet Applications (*n*) and Failures

Tourniquet	*n*	Failure Type	
		Mechanical	Application
CAT	40	1	0
MAT	40	2	0
OHT1	17	0	0
OHT2	23	0	1
QUICK	40	12	0
TK	40	1	0

APPLICATION TIMES

It is important to note that the application times in this report do not include time required to retrieve the tourniquet from stowage and remove it from its packaging. Thus, the present application times underestimate the total time required in the field to retrieve and apply any of the tourniquets. In addition, the observed application time variabilities exceeded the estimate used to determine sample size for the trials. This outcome, in combination with data lost due to mechanical failures, reduced the statistical power of inferential tests on application times to levels that were considerably lower than 0.80.

Except for the mechanical and application failures enumerated in Table 3, subjects were able to apply the tourniquets to all extremities within a reasonable amount of time (range: 24–204 s; see Fig. 3). No reliable trends in mean application times were observed over test days (Fig. 4), and subjects were able to successfully apply tourniquets with one hand to the opposite arm irrespective of hand dominance (Fig. 5). However, the box plot of CAT application times in Figure 4 shows that the dispersion of those times decreased as the trials advanced. Additional CAT training might reduce the range of application times. Using the dominant hand in applying the CAT might also provide a slight advantage, but inferential analysis failed to detect a statistically significant difference between dominant and nondominant hand applications. Whether the use of the dominant or nondominant hand affects the times required to apply tourniquets to the lower extremities is unknown.

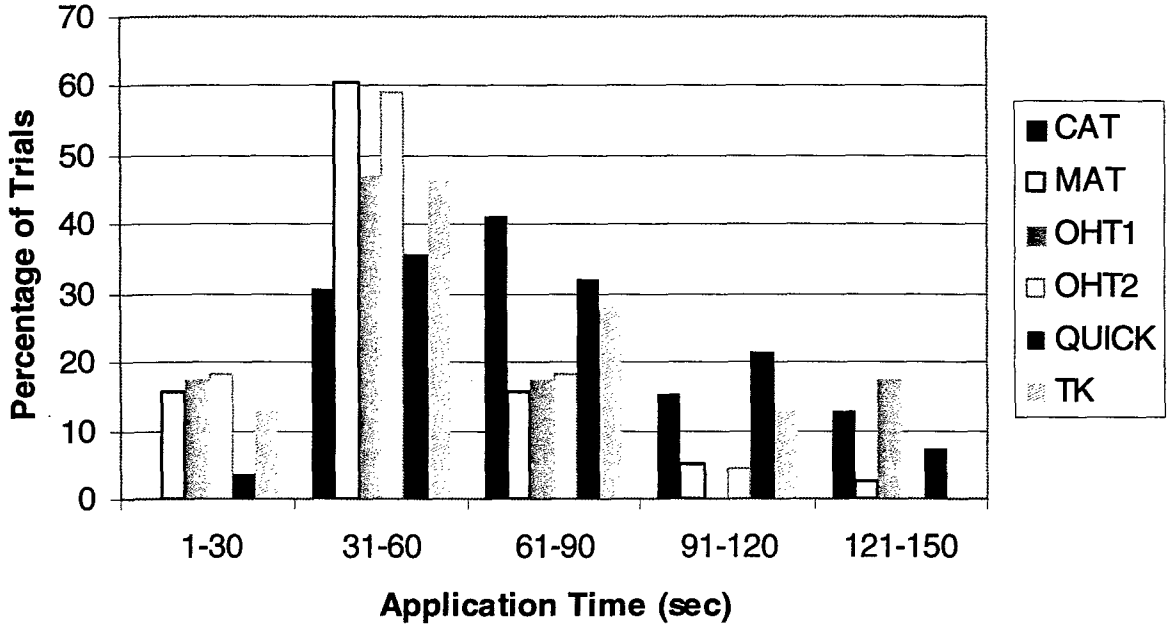

Figure 3. Percentage of tourniquet trials within arbitrarily selected 30-second application latency time intervals. Arm and leg applications are pooled since there were no statistical differences in mean application times between upper and lower extremities. Illustrated data are limited to trials in which the subject was able to apply the tourniquet within 150 seconds.

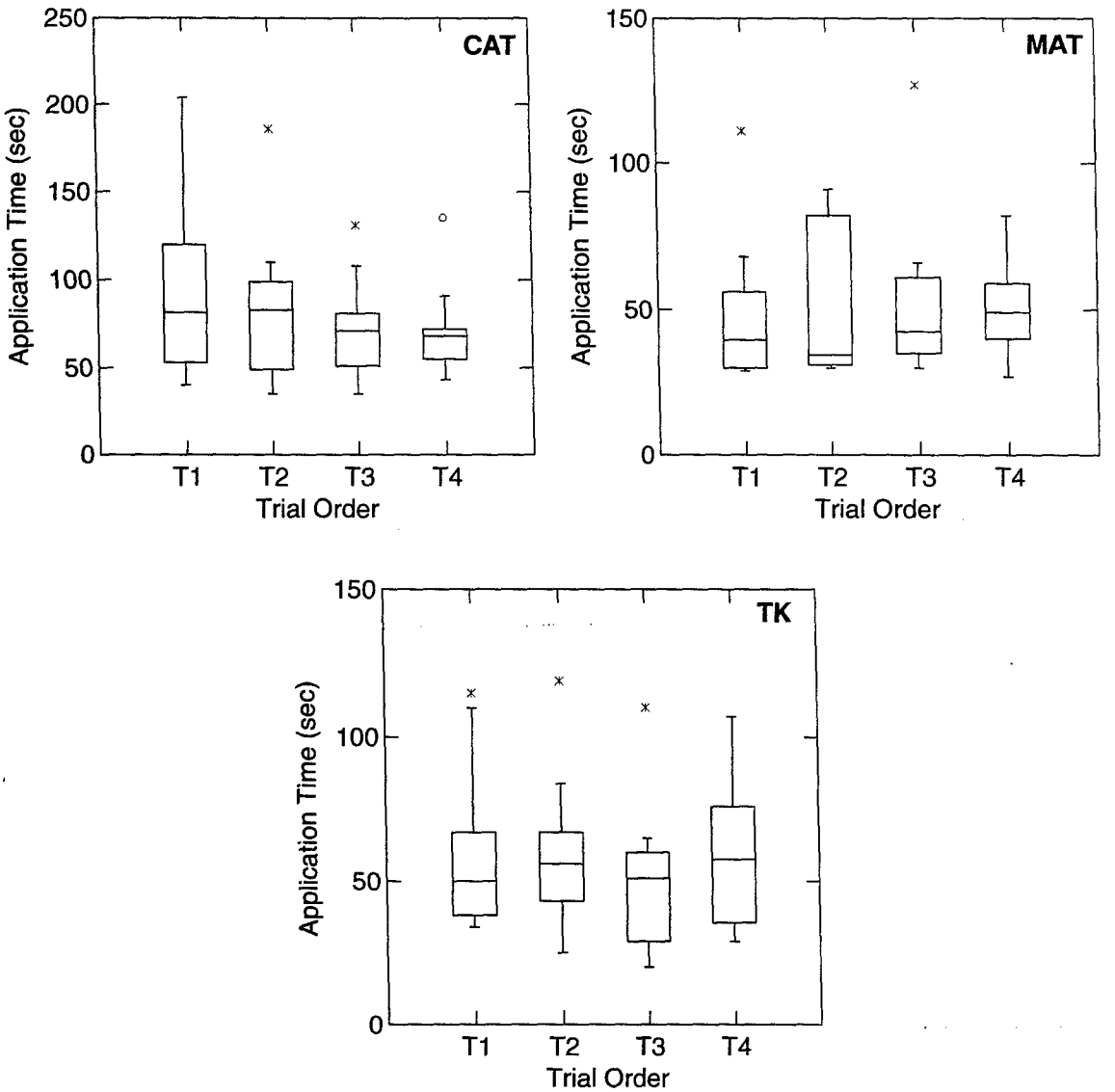

Figure 4. Application time box plots for three tourniquets (CAT, MAT, TK) as a function of trial order. The length of each box displays the range of values within the first and third quartiles. The horizontal line in each box denotes the median. The absolute difference between the first and third quartiles (Hspread) is used to define the remaining values in the plot. Vertical lines (whiskers) extending from each box show values that fall within 1.5 × Hspread. Asterisks and open circles identify outliers beyond the whiskers. An asterisk falls within 3 × Hspread, and an open circle falls outside this range. OHT1 and OHT2 trial order data were too incomplete to warrant inclusion here. QUICK is also excluded because of the small number of data points ($n = 4$) on the third trial. Illustrated data are limited to trials in which the subject was able to apply the tourniquet within the five minutes allowed.

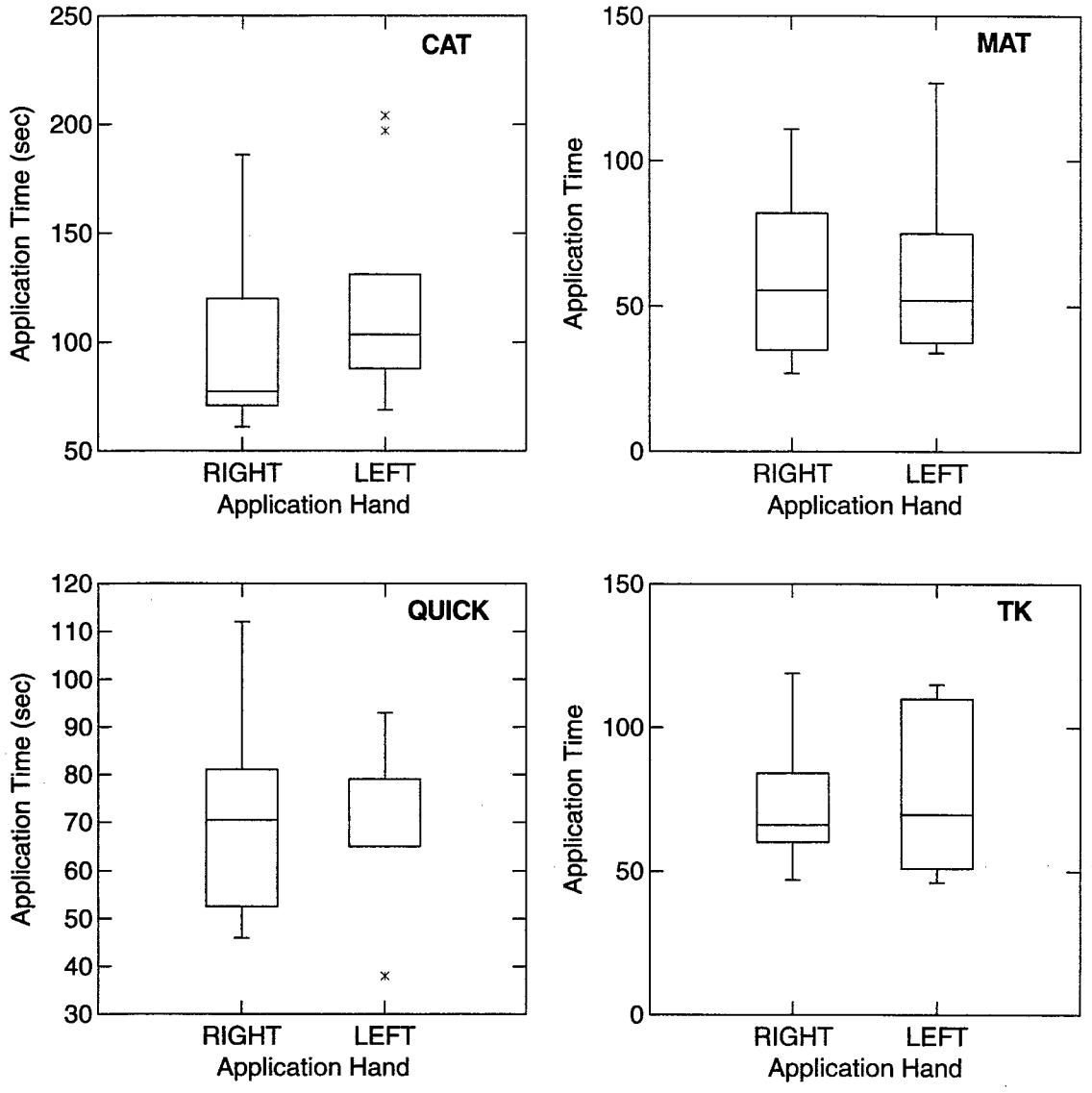

Figure 5. Application time box plots for four tourniquets (CAT, MAT, QUICK, TK) as a function of application hand dominance. All subjects reported that they were right-handed. See Figure 8 for an explanation of box plot features. OHT1 and OHT2 hand-dominance data were too incomplete to warrant inclusion. The median for QUICK is at the bottom of the box (65 s). Illustrated data are limited to trials in which the subject was able to apply the tourniquet within the five minutes allowed.

OCCLUSION OF ARTERIAL BLOOD FLOW

Doppler Stethoscope

The percentages of trials resulting in Doppler Flow and No-Flow calls for all tourniquets and limbs are illustrated in Figure 6. According to these calls, the OHT1 and QUICK tourniquets failed to occlude arterial blood blow in a majority (>80%) of trials, and the OHT2 failed to occlude arterial blood flow in >30% of trials.

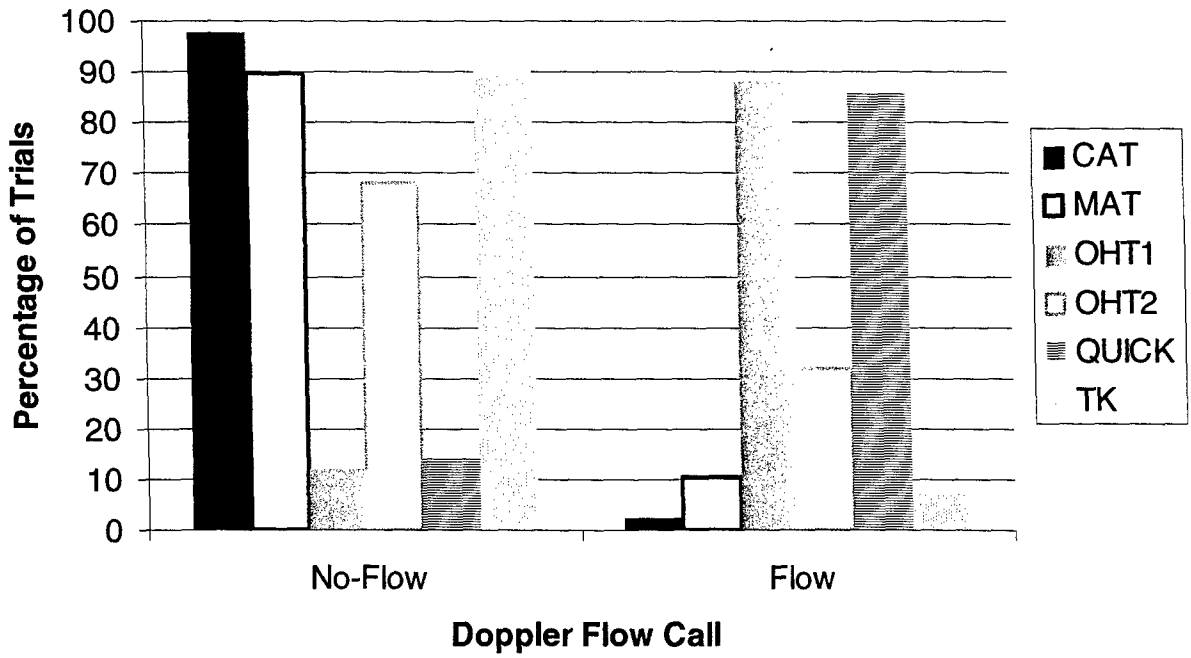

Figure 6. Percentage of Doppler flow calls for each tourniquet. "Flow" and "No-Flow" calls indicate the presence or absence of an auditory signal indicating pulsatile flow, respectively. Data from upper and lower limbs are combined in this illustration. Illustrated data are limited to trials in which the subject was able to apply the tourniquet within the five minutes allowed.

Impedance Plethysmography

Data from a total of 156 trials were included in the IPG analyses. Data from a given trial were included if they had fairly stable impedance, EKG, and Doppler recordings in both the START and END sequences. Data from a given trial were excluded if impedance, EKG, or Doppler records were lost or corrupted by excessive motion artifact during START and/or END sequences, or if the subject failed to complete application of the tourniquet.

Figure 7 shows a time-compressed graph of data typical of that obtained during the test trials. The illustrated test case was one in which tourniquet application resulted in disappearance of the Doppler blood flow signal, while IPG indicated that arterial occlusion was incomplete (Figs. 8 and 9).

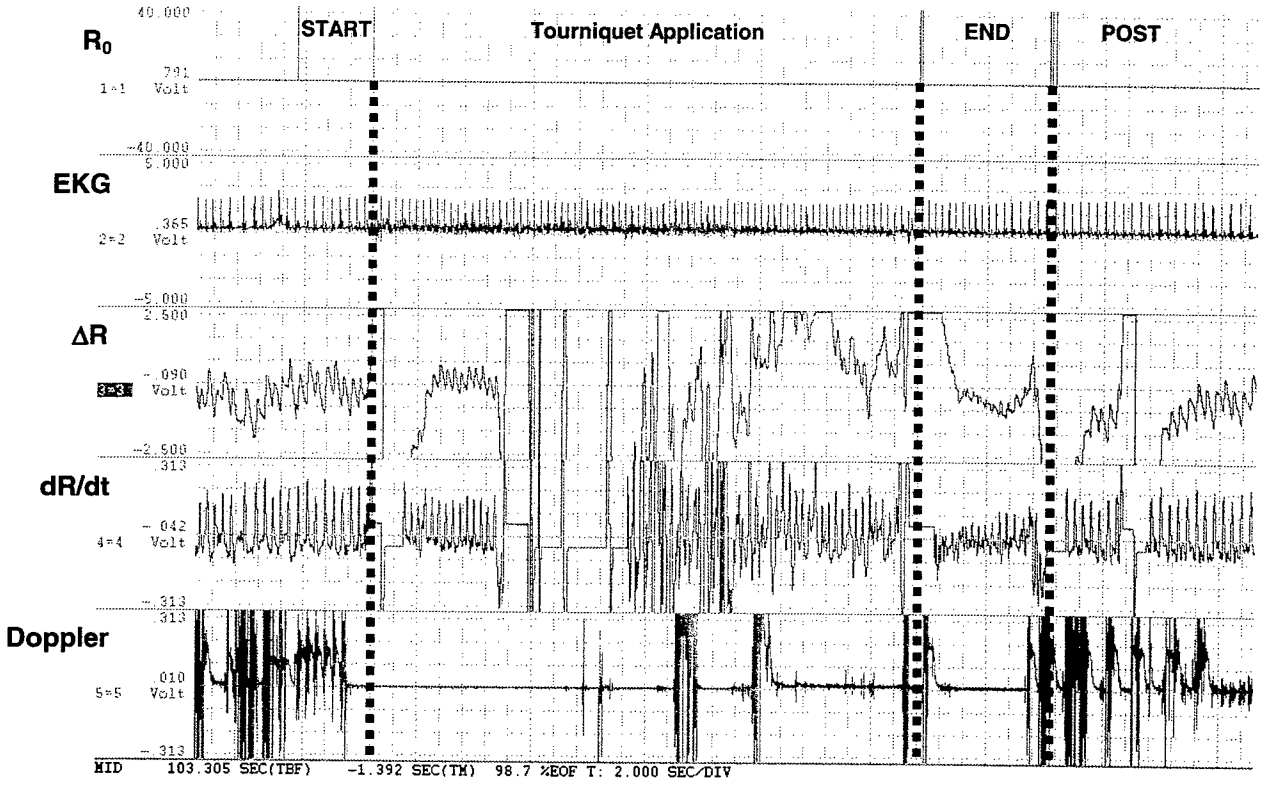

Figure 7. Time-compressed WinDaq presentation of a typical tourniquet trial on a leg (02MATRL050518). Dotted vertical lines overlay the figure to extend event marks in the top trace through all traces. The five impedance plethysmographic data traces from a tourniquet trial completed under ideal laboratory conditions. From top to bottom: Ro and event marks, EKG, ΔR, dR/dT, and Doppler blood flow velocity. Progress through the trial sequence is denoted by the event marks in the top trace. Dotted vertical lines overlay the figure to extend event marks in the top trace through all traces. A baseline period was established between the start of the recording period and the first single event mark in the top trace. The tourniquet was then applied and tightened in the subsequent period between the two single event marks. The tourniquet remained tight between the right single event mark and the following double event mark. The tourniquet was released after the double event marks.

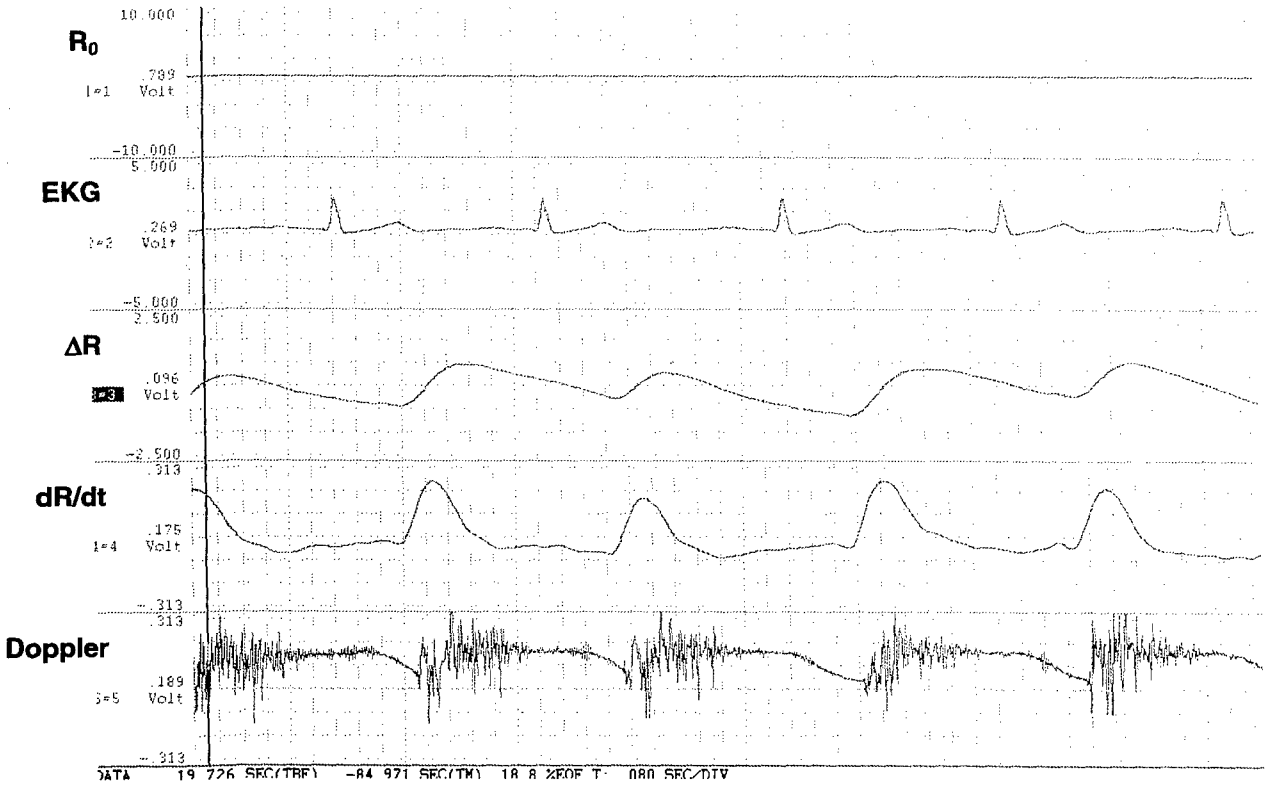

Figure 8. Uncompressed START section of the analyzed pulses for the trial in Figure 7.

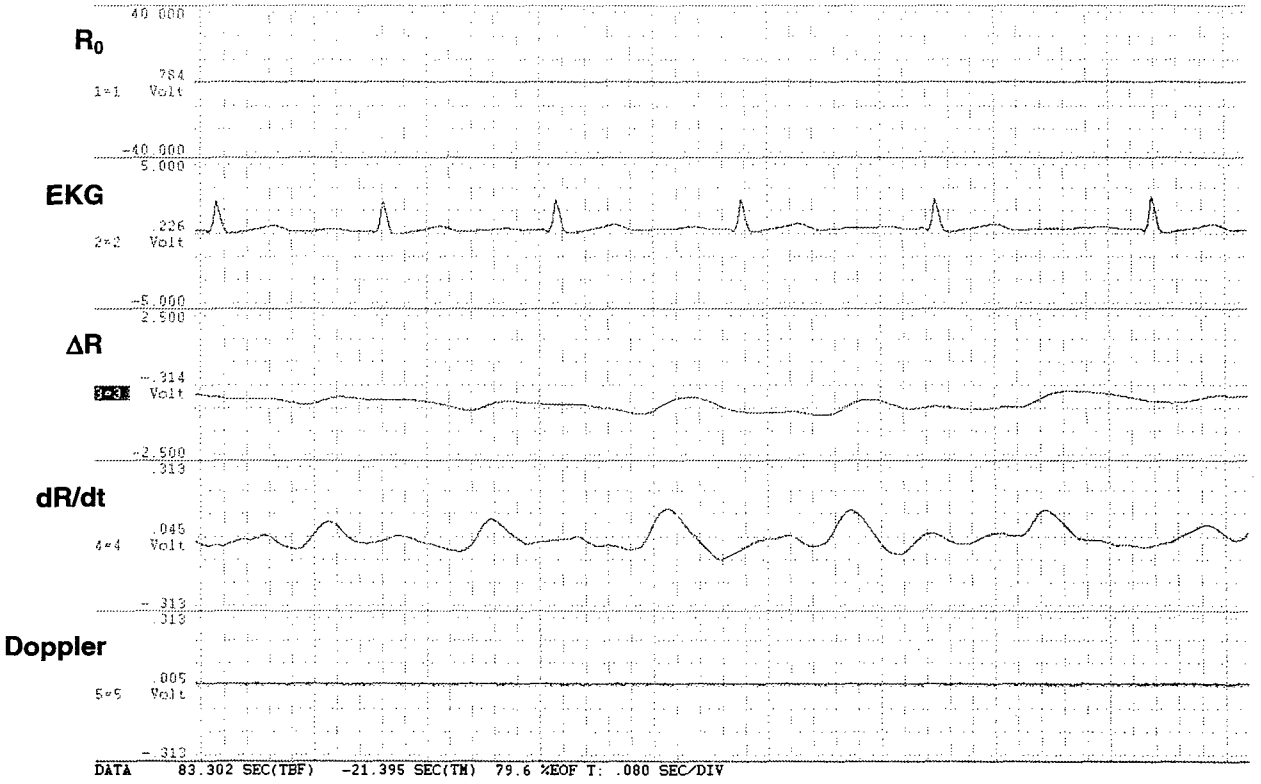

Figure 9. Uncompressed END section of the analyzed pulses for the trial in Figure 7. Note the presence of attenuated pulse waveforms in the impedance ΔR trace and the absence of pulsatile information in the Doppler trace.

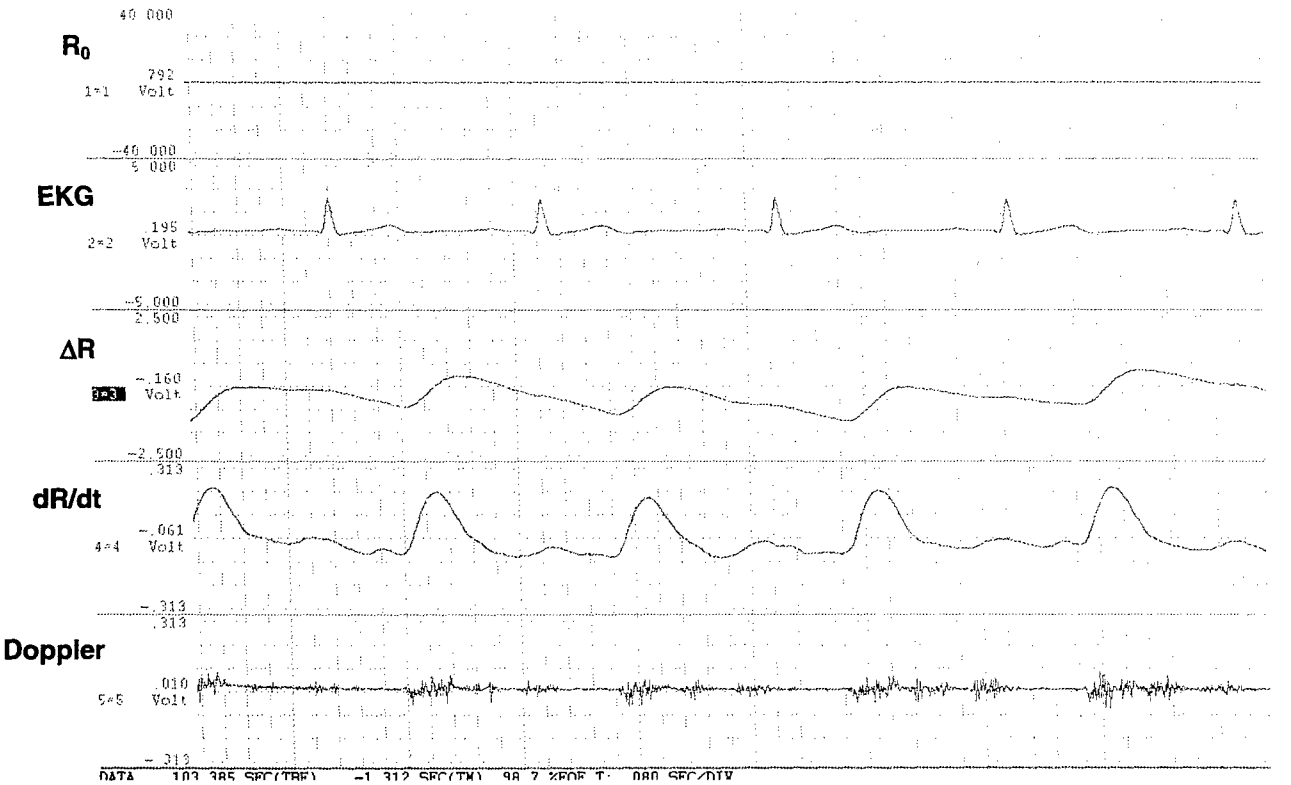

Figure 10. Uncompressed POST section of the analyzed pulses for the trial in Figure 7. Note that the ΔR pulses have returned to their baseline levels of oscillation but that the Doppler pulse waveforms remain attenuated in amplitude.

Figure 11 shows a time-compressed presentation of a tourniquet test that produced relatively noisy IPG data. Despite the noise in the waveforms, pulse sequences from the recording could be extracted and successfully analyzed (Fig. 12).

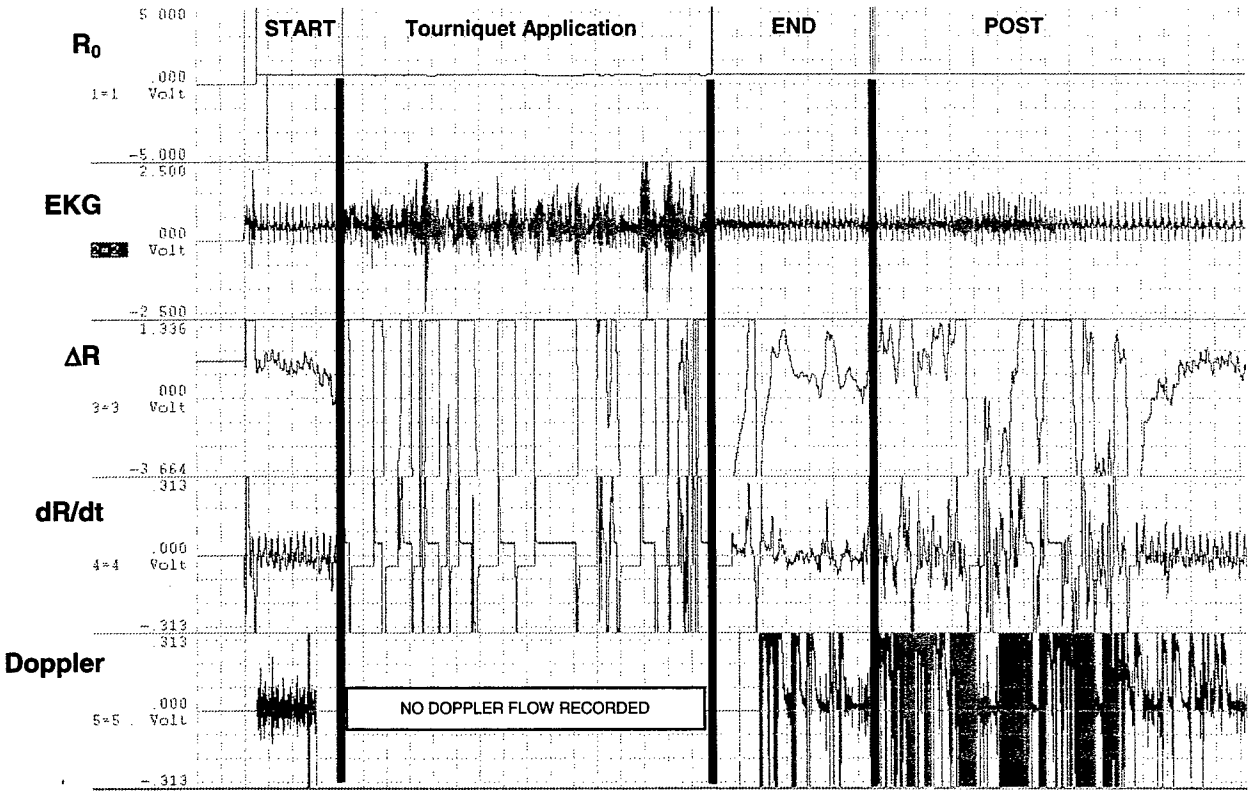

Figure 11. Time-compressed WinDaq presentation of a tourniquet test (09tkll050523) with noisy IPG data. Dotted vertical lines overlay the figure to extend event marks in the top trace through all traces.

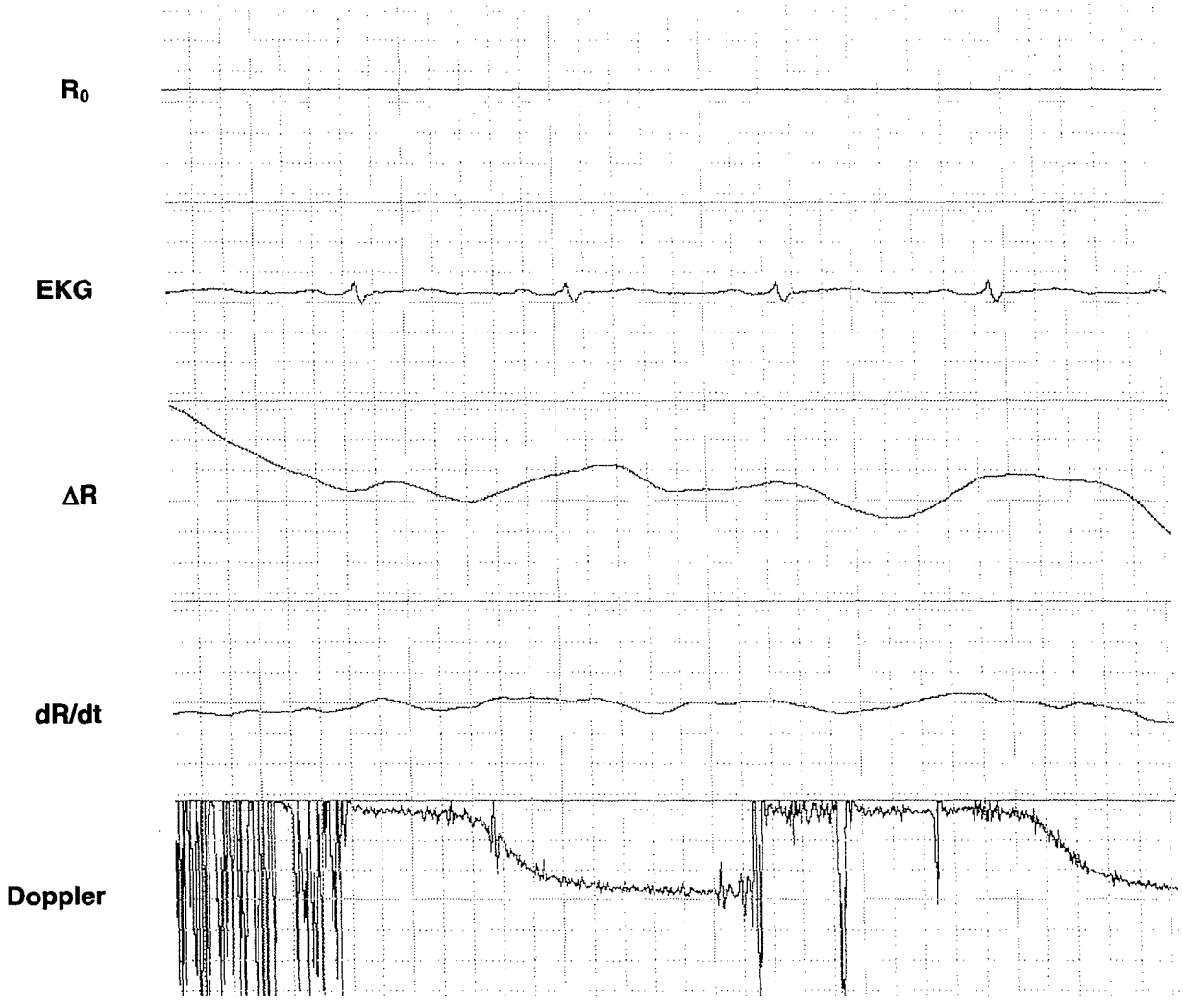

Figure 12. Uncompressed END sequence from the recording in Figure 11.

IPG blood flow was increased after tourniquet application in 38 trials, 35 of which resulted in occlusion failure by Doppler call (Table 4). Similar results have been reported in studies of compression bandages at application pressures below systemic diastolic pressure,[19] suggesting that the present increases were associated with occlusion pressures lower than diastolic. This finding is addressed in the Discussion section of this report (pg. 25) and has important ramifications on the battlefield: Improper tourniquet application may actually be counterproductive and may increase blood loss.

Table 4.
Number of Outcomes across IPG and Doppler Categories

Doppler	IPG		
	Decrease	No Change*	Increase
No-Flow	99	5	3
Flow	14		35

* Blood flow did not change because the tourniquet was not successfully applied.

The IPG blood flow determinations (see Appendices A and E) provided continuous measures that augmented the Doppler results. Figure 13 shows the frequency distribution of IPG-indicated efficacies of blood flow occlusion, with the corresponding Doppler No-Flow calls. The prevalence of Doppler No-Flow calls with IPG-indicated occlusion efficacies of only 20–80% (80–20% of initial flow remaining) indicates that IPG is a more sensitive measure of arterial blood flow than the Doppler signals.

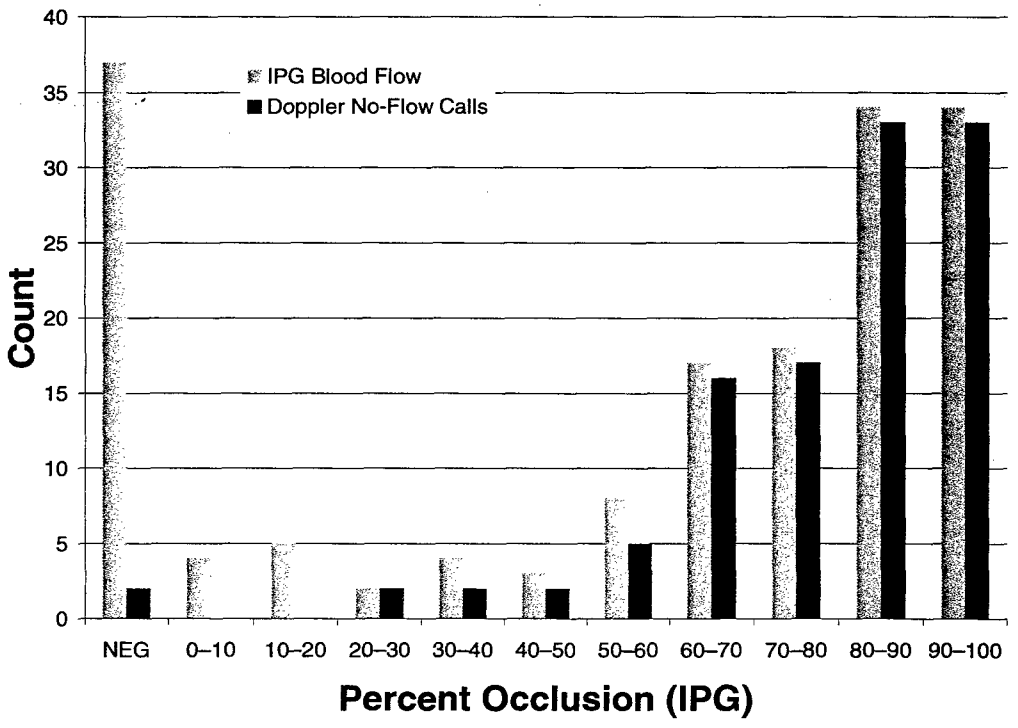

Figure 13. Frequency distributions of occlusion efficacy and corresponding Doppler No-Flow calls for all trials ($n = 166$) in which IPG blood flow data were successfully acquired. The bin labeled "NEG" gives the counts for cases in which IPG blood flow was *increased* after tourniquet application. Substantial IPG blood flow (20–80%) remained in large numbers of trials for which Doppler No-Flow calls were made.

This sensitivity is probably due at least in part to the dependence of IPG-indicated blood flow on heart rate, while Doppler indications of blood flow are dependent only on pulsatile properties. High frequency but low amplitude pulses may be missed with Doppler techniques, but manifest in measurable IPG blood flow by the product of pulse properties times heart rate (See Appendix A, Eq. A6). Indeed, subject heart rates after tourniquet application (Table 5) tended to be relatively high due to the preceding exercise, but no striking relationships emerged between Heart Rate, % Occlusion, and Doppler Flow or Doppler No Flow.

Table 5.
Heart Rate vs. Percent Occlusion from IPG Blood Flow Measurements and Doppler Flow/No-Flow Calls

	Heart Rate, beats/min*	
% Occlusion, IPG	Doppler No-Flow	Doppler Flow
<0	92.8	105.0
0–10	---	99.3
10–20	---	108.0
20–30	114.4	
30–40	110.6	115.0
40–50	96.0	100.2
50–60	98.3	105.9
60–70	105.1	98.7
70–80	103.1	73.4
80–90	98.3	112.7
90–100	101.2	123.3

* Mean of individual values in category

Figure 14 shows the percent occlusion data from Figure 13 broken out for each of the tourniquets tested.

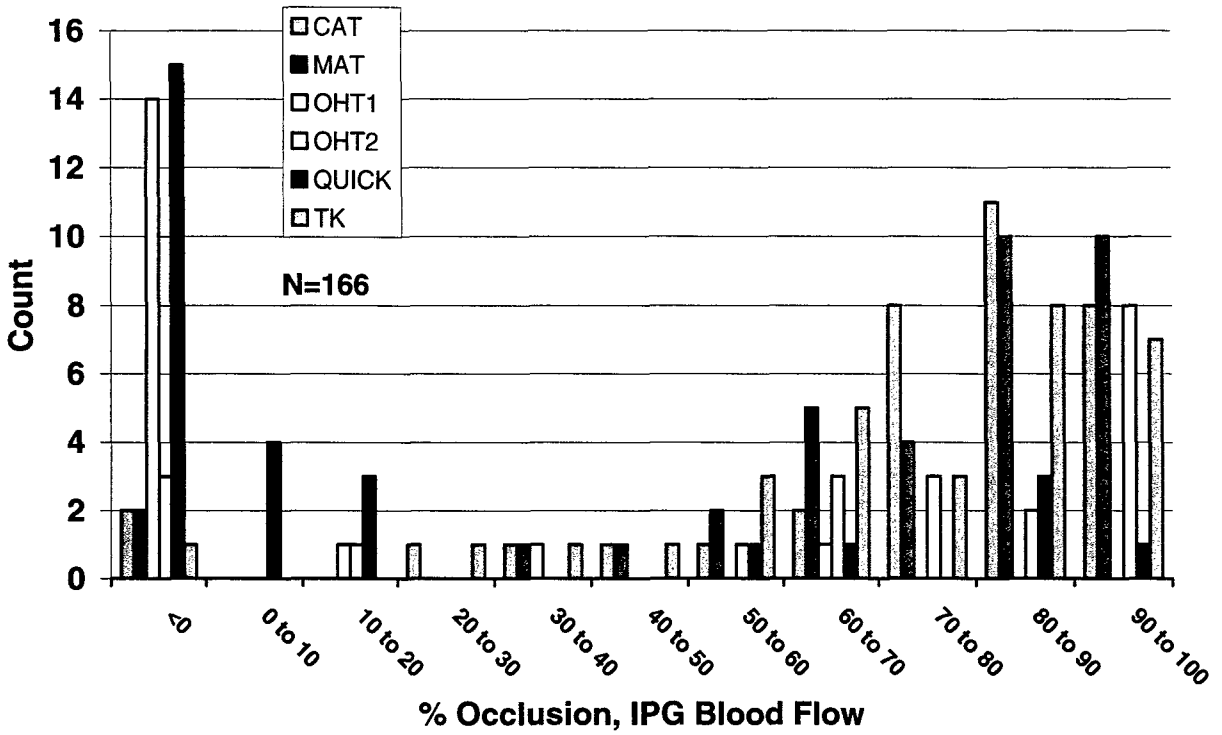

Figure 14. Frequency distributions of IPG-indicated occlusion efficacies of the individual tourniquets tested. (IPG data in Figure 13 broken out by tourniquet.)

Figure 15 illustrates the percentages of arterial occlusion achieved in the upper and lower extremities with the fully applied tourniquets as indicated by IPG. The occlusion efficacies of the CAT, MAT, OHT2, and TK were statistically indistinguishable. The QUICK had difficulty occluding lower extremities and was inconsistent at occluding upper extremities.

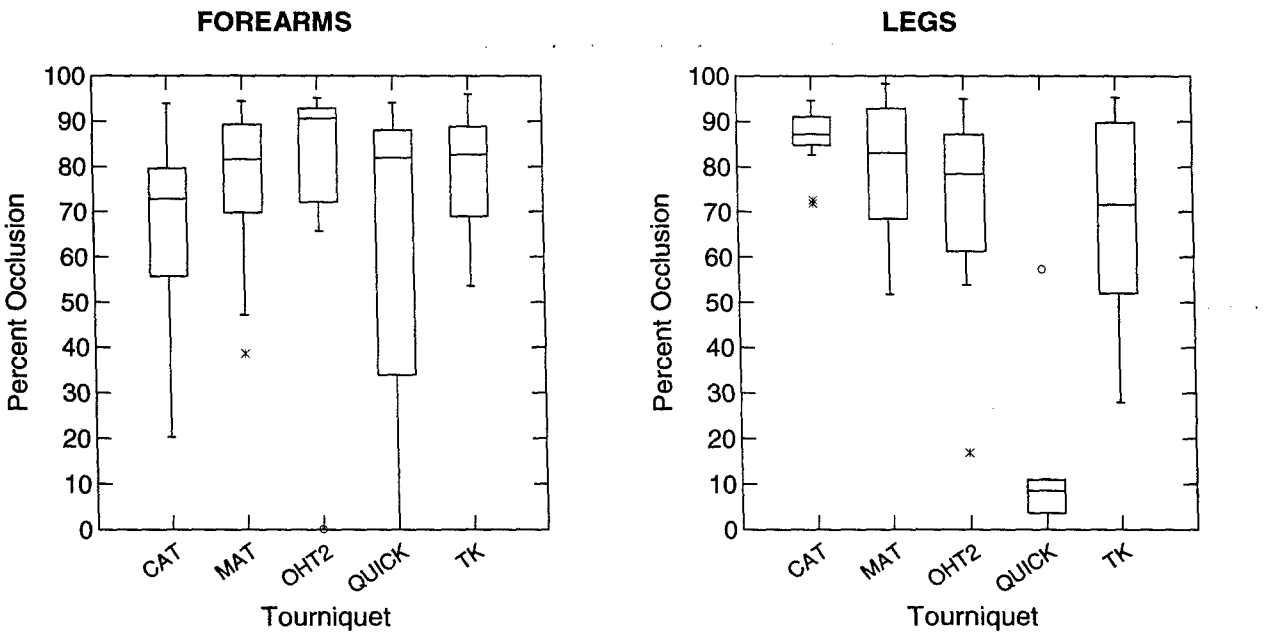

Figure 15. Percentage of arterial occlusion indicated by IPG in forearms and legs. See Figure 4 for an explanation of box plot features. Postapplication IPG blood flows were decreased in too few OHT1 trials ($n = 3$) to warrant inclusion here. Illustrated data for the other tested units are limited to trials in which postapplication IPG blood flows were decreased.

Blood flow determinations for OHT2 were interesting given this tourniquet's Doppler results. Despite the fact that Doppler flow calls indicated the presence of pulsatile flow (i.e., failure to occlude) in over 30% of OHT2 trials, IPG analysis indicated that the OHT2 was fairly effective at occluding blood flow in trials in which post-application IPG blood flows were decreased.

HUMAN FACTORS

In an earlier report,[4] Special Operations corpsmen identified *arterial occlusion*, *quick application*, *light weight*, and *compact design* as the top four requirements for a combat-deployable self-applied tourniquet. Table 6 lists the physical dimensions and weights of the tourniquets evaluated in this report. The MAT and OHT2 are at least two times heavier than the other tourniquets, and the MAT and QUICK occupy the most stowage volume.

Table 6.
Tourniquet Dimensions and Weights

Tourniquet	Dimensions (in)	Volume (in^3)	Weight (gm)
CAT	6.5 x 1.75 x 2.25	25.6	59.5
MAT	4.0 x 2.5 x 4.25	42.5	113.4
OHT1	5.0 x 1.25 x 2.5	15.6	62.8
OHT2	5.25 x 2.0 x 2.25	23.6	115.8
QUICK	8.5 x 2.75 x 1.75	40.9	44.0
TK	3.5 x 1.0 x 2.0	7.0	47.1

At the conclusion of the present study, subjects ranked the six tourniquets on the basis of their subjective impressions of user friendliness, ease of application while users were blindfolded, and comfort. The rank R ascribed by a subject to a given tourniquet ($R = 1$ "Best"; $R = 6$ "Worst") was converted into a Score = $(N+1) - R$, where $N = 6$ was the number of tourniquets. Totals for the ten individual subject scores for each tourniquet are shown in Figure 16.

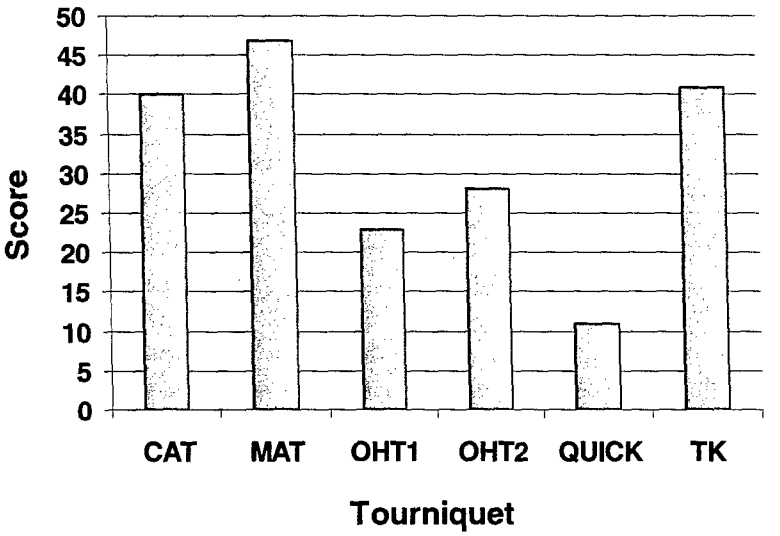

Figure 16. Totals of subjective rank scores assigned by the test subjects to the six tourniquets evaluated in this work.

DISCUSSION

The QUICK had an unacceptably high mechanical failure rate (30%) due to the jamming or stripping of gears that tighten this tourniquet (Appendix B). Because no mechanical failures occurred when the QUICK was applied without fouling by blood analog and sand during the training runs, we attribute its mechanical failures in the full trials to the buildup of sand in the gears during tourniquet preparation and application.

Tourniquet application times varied more widely than anticipated, a result that may be related to a number of variables including limited training of subjects, blindfolding of subjects during tourniquet application, and tourniquet fouling with sand-impregnated blood analog solution before application. If the tourniquets did not fail by mechanical malfunction, the vast majority of trials were completed with tourniquet application times of three minutes or less. Only one trial resulted in an application failure (i.e., an application time exceeding the 5-minute time limit). Thus, self-application of tested tourniquets was completed within clinically acceptable time frames affording significant time savings in comparison to the traditional method of waiting for medical personnel to arrive. To use tourniquet application time to measure ease of use, future studies following a similar methodology will require a considerably larger sample size to achieve a requisite level of statistical power for pairwise comparisons.

The occlusion efficacies of the CAT, MAT, OHT2, and TK were statistically indistinguishable. None emerged superior to the others solely on the basis of ability to occlude blood flow. However, the OHT1 and QUICK were clearly inefficient at occluding blood flow in trials during which these tourniquets were successfully applied within the 5-minute time limit.

Measurement of blood flow by both IPG and Doppler stethoscope proved to be a critical aspect of our methodology. Comparisons between IPG and Doppler flow calls revealed

that IPG is the more sensitive measure of arterial occlusion efficacy. For example, Figure 13 indicates that Doppler No-Flow calls were made when IPG indicated that substantial blood flow (20–40%) remained. Table 10 indicates that Doppler Flow calls occurred in more than 30% of OHT2 trials. Upon closer inspection, IPG revealed that the occlusion efficacy of the OHT2 was comparable to those of the CAT, MAT, and TK, all of which had a percentage of trials resulting in Doppler No-Flow calls near or exceeding 90%.

Figure 13 also shows that IPG blood flow was *increased* after tourniquet application in 38 trials, 35 of which also failed by Doppler call. This unexpected increase would not have been detected had we simply recorded Doppler calls as in previous studies. Similar results have been reported in studies of compression bandages at application pressures below systemic diastolic pressure,[19] results suggesting that our increases were associated with occlusion pressures lower than diastolic. Results suggest that tourniquet application may evoke a relatively complex series of responses beyond those resulting from hemorrhage. Such responses may be related to the signals that govern the cardiovascular responses to exercise and pain, which together may exert important effects on peripheral vasoconstriction, cardiac contractility, venoconstriction, and the distribution of venous blood. They may also result in important changes in blood pressure and heart rate modulated by the autonomic nervous system. Such changes include:

- central command, the motor outflow from the cerebral cortex in response to apparent exertion;
- the mechanoreflex originating from activated mechanosensors from exertion during application of the tourniquet;
- the metaboreflex (muscle chemoreflex) caused by chemical stimulation of sensory afferents within the muscle, since dynamic exercise of a limb with its circulation arrested (i.e., partially occluded by a tourniquet) is a powerful stimulus for hypertension produced in response to metabolites trapped within the limb after exercise; and
- pain response: the ischemic pain response is one of the classic mechanisms for nociceptor-induced pressor responses

Increased blood flow associated with incomplete tourniquet application may have important ramifications on the battlefield: improper tourniquet application may actually increase blood loss.

CONCLUSIONS AND RECOMMENDATIONS

1. All tourniquets except the OHT1 and QUICK performed reasonably well on arms and legs, with median occlusion efficacies exceeding 70%. The occlusion efficacies of the OHT1 and QUICK were poor or inconsistent.

2. The QUICK had an unacceptably high mechanical failure rate (30%).

3. The occlusion efficacies of the CAT, MAT, OHT2, and TK were statistically indistinguishable. These tourniquets also had low mechanical failure rates and clinically acceptable application times.

4. The MAT and OHT2 are two or more times heavier than the other tested tourniquets, while the MAT and QUICK occupy the most stowage volume.

5. Using subjective impressions, test subjects ranked the MAT as their overall favorite, followed closely by the TK and the CAT. Subjects ranked the other three tourniquets substantially lower.

6. Familiarization training should accompany deployment of any self-applied tourniquet, because simple perusal of the instructions provided by the manufacturer is insufficient to ensure proper application when the need arises.

7. Additional research is recommended to investigate increases in blood flow that appear to occur with inadequate tourniquet application.

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APPENDIX A

IMPEDANCE PLETHYSMOGRAPHY DATA ANALYSIS

As presented by the WinDaq Waveform Browser, an example of the five traces recorded during an upper extremity tourniquet trial is shown in Figure A1: forearm base electrical resistance (Ro) and event marks, electrocardiogram (EKG), forearm electrical resistance changes (ΔR), first derivative of forearm electrical resistance changes (dR/dT), and forearm Doppler blood flow velocity.

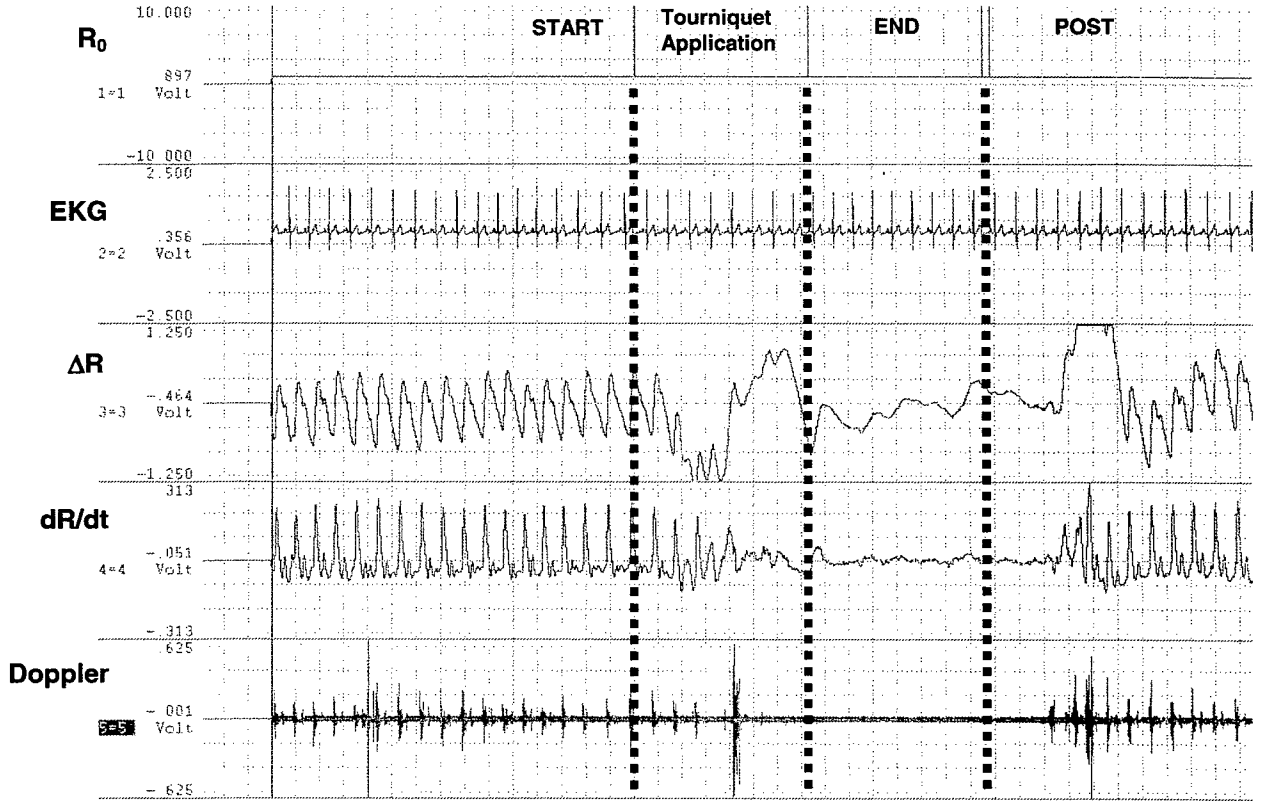

Figure A1. The five impedance plethysmographic data traces from a tourniquet trial completed under ideal laboratory conditions. From top to bottom: Ro and event marks, EKG, ΔR, dR/dT, and Doppler blood flow velocity. Progress through the trial sequence is denoted by the event marks in the top trace. Dotted vertical lines overlay the figure to extend event marks in the top trace through all traces. A baseline period was established between the start of the recording period and the first single event mark in the top trace. The tourniquet was then applied and tightened in the subsequent period between the two single event marks. The tourniquet remained tight between the right single event mark and the following double event mark. The tourniquet was released after the double event marks.

This trial was completed under ideal laboratory conditions with the subject lying quietly in a supine position while the tourniquet was applied and tightened by a technician until total disappearance of the wrist Doppler auditory sounds. Selected subsegments of the

labeled START, END, and POST segments of this run, analogous to segments of the same names described in the Methods/Procedures section in this report, are illustrated in Figures A2–A4.

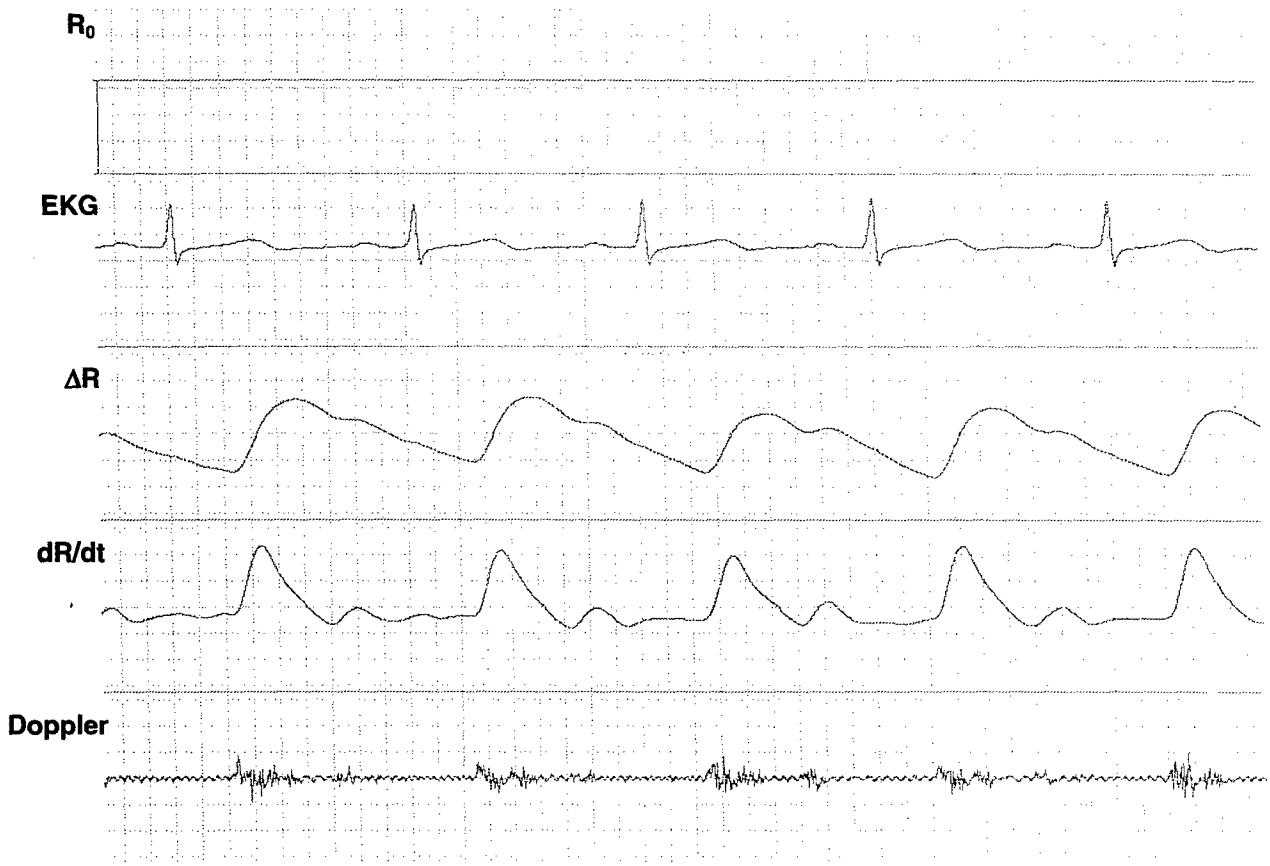

Figure A2. Selected START sequence from Figure A1. Note the fully developed blood flow waveforms (Trace 3) and the corresponding Doppler signals for each cardiac cycle (Trace 5).

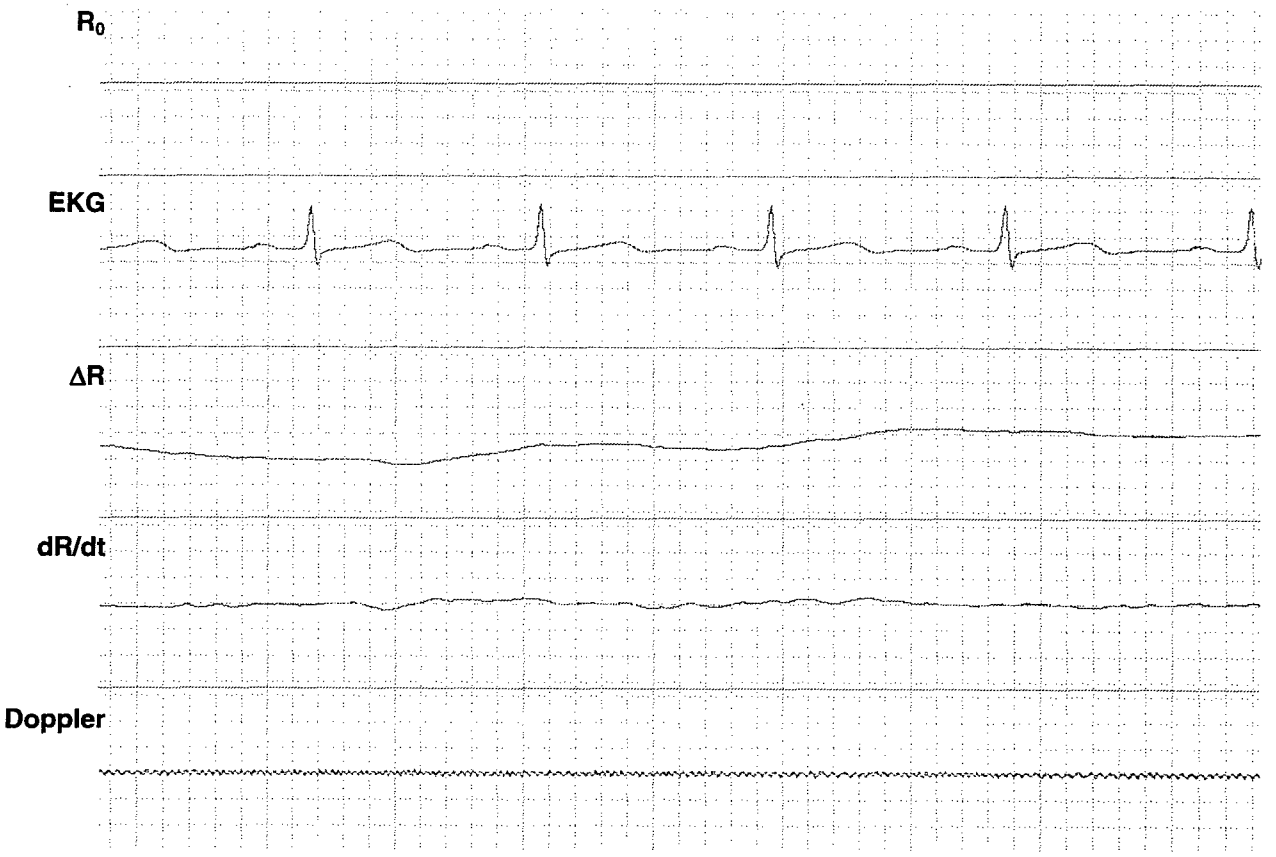

Figure A3. Selected END sequence from Figure A1. Note the absence of a Doppler waveform (Trace 5) and the remaining, but markedly attenuated, impedance ΔR waveform (Trace 3).

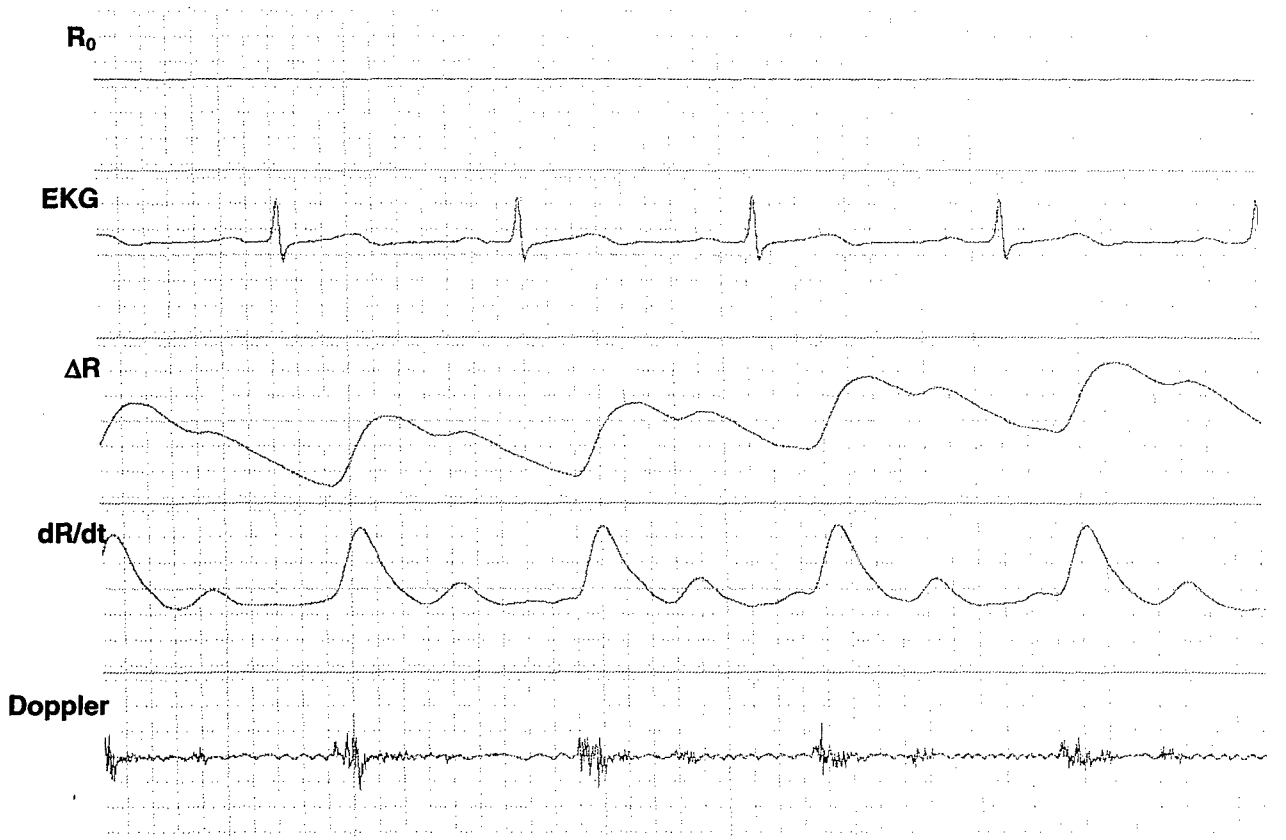

Figure A4. Selected POST sequence from Figure A1. Note that the amplitudes of the impedance ΔR pulse waveforms (Trace 3) are increased from those in the START period due to reactive hyperemia after tourniquet release and that the Doppler signals (Trace 5) are reestablished.

Quantitative measures of monitored segment blood flow and hemodynamic status were computed ex post facto from the START, END, and POST segments of each tourniquet trial suitable for analysis with a custom program, Rheoencephalographic Impedance Scanning System (RheoSys), developed by LDM Associates. The analysis proceeds from a graphical display of the overall impedance ΔR and EKG traces. The operator first selects individual impedance pulse waveforms from which blood flow and other hemodynamic parameters are to be computed. RheoSys then proposes the placement of seven vertical reference lines in each selected pulse waveform, as illustrated for one selected pulse in Figure A5. The seven lines mark the following features of the selected pulse waveform:

1. Peak of the EKG QRS complex immediately preceding the selected IPG pulse,
2. Start of the systolic upslope of the IPG pulse,
3. Maximum amplitude of the IPG pulse,
4. Position of the dicrotic notch in the IPG pulse,
5. Maximum amplitude of the postdicrotic segment of the IPG pulse,
6. Peak of the EKG QRS complex immediately after the systolic upslope of the selected IPG pulse, and
7. Start of the systolic upslope of the next IPG pulse.

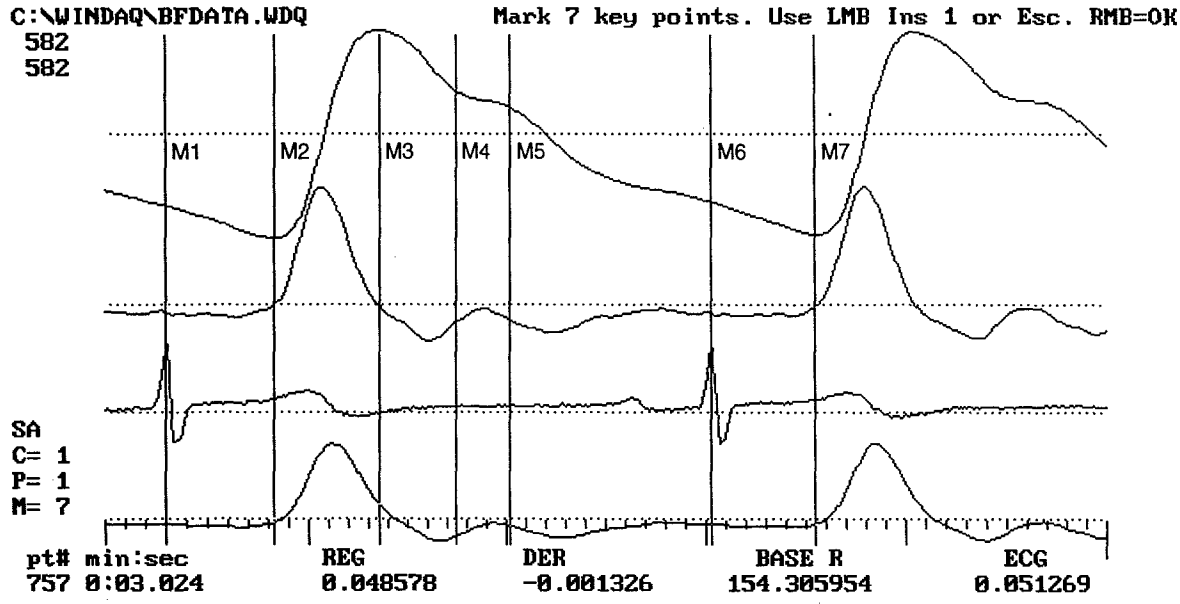

Figure A5. Landmarks in an impedance pulse, marked by vertical lines labeled M1, M2,...,M7. Traces from top to bottom: IPG ΔR waveform, calculated first derivative of the ΔR waveform (dR/dt) in the top trace, EKG waveform, and dR/dt waveform provided directly by the THRIM hardware. (Only the dR/dt waveform computed from the IPG ΔR waveform is used in RheoSys.) The horizontal dotted line in the computed dR/dt trace is the dR/dt = 0 line. The time at each landmark is t_{M1}, t_{M2}, ..., and t_{M7}, respectively, and the corresponding IPG ΔR amplitude is R_{M1}, R_{M2}, ..., and R_{M7}, respectively.

After the operator either accepts or adjusts the placement of these reference lines, the times and IPG ΔR signal amplitudes at the lines are used to calculate the following cardiovascular and hemodynamic parameters for each pulse:

HR (beats/min) Heart rate $= 60/(t_{M6} - t_{M1})$, (A1)
with t_{M1} and t_{M6} in seconds.

A (Ohm) Rheographic index of maximum systolic pulse amplitude given by

$$A = R_{M3} - \frac{(t_{M3} - t_{M2}) \cdot (R_{M7} - R_{M2})}{(t_{M7} - t_{M2})} \quad \text{(A2)}$$

ST (Ohm-seconds) Total area under the selected IPG pulse waveform from the start of the pulse at t_{M2} to the start of the next pulse at t_{M7}:

$$ST = \sum_{i=j}^{k} R_i \Big/ Sr - 0.5 \cdot (R_{M7} - R_{M2})(t_{M7} - t_{M2}) \quad \text{(A3)}$$

where j is the index for the IPG resistance datum at t_{M2}, k is the corresponding index at t_{M7}, and Sr is the sample rate (s^{-1}).

R_0 (Ohm) — Average base resistance of the monitored segment during the IPG pulse given by

$$R_0 = 0.5 \cdot (R_{M2} + R_{M7}). \quad \text{(A4)}$$

EXHT (Ohm) — Extrapolated IPG pulse amplitude given by Nyboer (1970) back-projection:

$$EXHT = (R_{M4} - R_{M2}) + (t_{M4} - t_{M2})(R_{M3} - R_{M4})/(t_{M4} - t_{M3}) \quad \text{(A5)}$$

BFA (ml/min) — Absolute segmental blood flow given by

$$BFA = HR \cdot EXHT \cdot \rho \cdot L^2 / R_0^2, \quad \text{(A6)}$$

where ρ is the specific resistivity of blood [150 Ohm-cm (Mohapatra, 1981)] and L (cm) is the separation distance between the two segmental sensing electrodes.

BF (ml/min·ml) — Normalized segmental blood flow given by

$$BF = BFA / Vg, \quad \text{(A7)}$$

where $Vg = C^2 L / 4\pi$ is the segmental geometric volume with C (cm) as the measured maximum circumference of the monitored segment.

PTT (s) — Pulse transit time $= (t_{M2} - t_{M1})$, (A8) in relation to the time interval between the EKG QRS complex immediately preceding the selected IPG pulse and the start of the selected IPG pulse (Nitzan et al., 2002).

TIN (s) — Time of excess arterial inflow $= (t_{M4} - t_{M1})$, (A9) the time period from start of the IPG pulse until the occurrence of the dicrotic notch (Wu, 1992).

TOUT (s) — Time of excess venous outflow $= (t_{M7} - t_{M4})$, (A10) the time period from the dicrotic notch until the end of the IPG pulse (Wu, 1992).

Note that A, ST, and EXHT are measures of pulse morphology independent of heart rate. In contrast, BF includes the influence of heart rate, which was found to be substantially increased during the occlusion (END) period in some trials.

The calculated output parameter values from *RheoSys* were stored in Excel spreadsheet format for statistical analysis.

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APPENDIX B

DESCRIPTIONS OF MECHANICAL FAILURES

Subject	Test Day	Tourniquet	Extremity	Description
1	1	QUICK	RIGHT ARM	gears stripped
10	1	QUICK	RIGHT ARM	gears stripped
7	2	MAT	RIGHT ARM	cable inside turnkey mechanism broke; strap appeared to loosen during turnkey operation
2	2	QUICK	RIGHT LEG	gears jammed
6	2	MAT	RIGHT ARM	cable inside turnkey mechanism broke; strap appeared to loosen during turnkey operation
5	2	QUICK	RIGHT LEG	gears jammed
3	3	QUICK	LEFT LEG	gears jammed
7	4	QUICK	LEFT ARM	gears jammed
2	4	QUICK	LEFT ARM	gears stripped
2	4	CAT	LEFT LEG	Windlass strap broke
6	4	QUICK	RIGHT ARM	gears jammed
1	5	QUICK	LEFT LEG	gears stripped
2	5	QUICK	RIGHT ARM	gears jammed
5	5	QUICK	RIGHT ARM	gears jammed
5	5	TK	RIGHT LEG	elastic band ripped
6	6	QUICK	LEFT LEG	gears stripped; clasp broke

APPENDIX C

POSTAPPLICATION SUBJECT NARRATIVES

TOURNIQUET	SUBJECT	EXTREMITY	COMMENTS
CAT	2	LEFT ARM	Application was easy. Only difficulty was turning the stick and kept getting caught on camis. Easy to use.
CAT	2	LEFT LEG	Turning the stick ripped the strap and the stick broke.
CAT	2	RIGHT ARM	Application was easy. Only difficulty was turning the stick and kept getting caught on camis. Easy to use.
CAT	2	RIGHT LEG	Application was easy. Easier with two hands. Blood flow restricted.
CAT	6	LEFT ARM	Easy to apply. Did stop blood flow.
CAT	6	LEFT LEG	It was easy to apply and the wrenching mechanism was at the right place and the right time, and it stopped blood flow. I feel this is one of the better ones.
CAT	6	RIGHT ARM	Application was easy, hard to wrench down, but did cut off blood flow.
CAT	6	RIGHT LEG	The tourniquet was easy to install with two hands, the wrenching mechanism was in the right spot at the right time.
CAT	5	LEFT ARM	I thought it was good until the point of securing it in place.
CAT	5	LEFT LEG	Easy application, no difficulties.
CAT	5	RIGHT ARM	Found it easy to apply and tighten.
CAT	5	RIGHT LEG	Easy to apply, effective tourniquet.
CAT	10	LEFT ARM	Hard to tightened and hard to secure blindfolded.
CAT	10	RIGHT LEG	NO COMMENTS
CAT	10	LEFT LEG	Very easy to slide over the leg, but actually winching up the windless, it was slippery and hard to put into the holder.
CAT	10	RIGHT ARM	Works quickly, hard to secure.
CAT	8	LEFT ARM	I thought it was hard to apply but probably effective.
CAT	8	LEFT LEG	NO COMMENTS
CAT	8	RIGHT ARM	I thought the windage was difficult to operate as you can only secure in 180 degree increments so it was either too tight, or not tight enough.
CAT	8	RIGHT LEG	Easy to apply.
CAT	4	LEFT ARM	Good tourniquet. Must maintain positive control of wand while applying. If you lose control you must start over. Velcro can prevent from securing.
CAT	4	LEFT LEG	Easier to apply with use of both hands. One benefit is sand in the mechanism doesn't interfere with the use of the device. Pain is significant, no happy medium.

TOURNIQUET	SUBJECT	EXTREMITY	COMMENTS
CAT	4	RIGHT ARM	Tourniquet was adequate. Some problems were the Velcro that secures the winching mechanism fell into place and made it difficult for me to get the stick into the groove once I had completed the revolutions. Other items to consider was I had to go a little bit past comfort or what I thought was adequate to complete full 180 degree rotation. It was too tight. Other thought, if you drop it or lose control, you have to start over.
CAT	4	RIGHT LEG	Easy application. Able to restrict blood flow. No need to over-tighten.
CAT	9	LEFT ARM	Last turn is hard to get, but does stop blood flow
CAT	9	LEFT LEG	Easy to apply with eyes closed or blindfold. The windless was easy to work on top of leg. Added extra turn and works well.
CAT	9	RIGHT ARM	Easy to apply and easy to cut off circulation. The clips are little difficult to get into place.
CAT	9	RIGHT LEG	Tightening caused the strap to rip.
CAT	3	LEFT ARM	NO COMMENTS
CAT	3	LEFT LEG	Worked pretty good, easy to use.
CAT	3	RIGHT ARM	Easy to put on, easy to turn.
CAT	3	RIGHT LEG	Easy to use.
CAT	1	LEFT ARM	Difficult to secure. Quick, easy application.
CAT	1	LEFT LEG	Very easy to use, simple mechanism, quick to adjust and good torque when applying it.
CAT	1	RIGHT ARM	Easy to apply. Difficulty in getting handle to clip into bracket to secure.
CAT	1	RIGHT LEG	No problems putting it on, easy to torque down.
CAT	7	LEFT ARM	Seemed to work well, but I had difficulty securing the bar into its locking position.
CAT	7	LEFT LEG	Easy to apply, easy to secure.
CAT	7	RIGHT ARM	Difficult to get tight using my left hand. The worst part was trying to get it secured; it kept coming undone.
CAT	7	RIGHT LEG	Easy to apply, easy to secure.
MAT	2	LEFT ARM	It was pretty easy to use, no difficulty on application. The only complaint is pinched skin. All in all, easy to use.
MAT	2	LEFT LEG	Application was easy. Restricted blood flow.
MAT	2	RIGHT ARM	Went on pretty easy, and didn't pinch my skin this time. I cranked down much more on the MAT than on the OHT with the same results.
MAT	2	RIGHT LEG	Easy to apply, even with both hands. Still pinches skin, but restricts blood flow.
MAT	6	LEFT ARM	It got a whole lot of skin, and hurt a little bit, but it stopped blood flow and was easy to use.
MAT	6	LEFT LEG	Application is easy, but once you begin to tighten it pinches the skin, and doesn't stop blood flow.

TOURNIQUET	SUBJECT	EXTREMITY	COMMENTS
MAT	6	RIGHT ARM	Tourniquet broke during application.
MAT	6	RIGHT LEG	Application was quick and easy. Latching mechanism broke, reinstalled and was successful.
MAT	5	LEFT ARM	Easy to use, easy to apply.
MAT	5	LEFT LEG	Hasp kept coming off the hook.
MAT	5	RIGHT ARM	Easy application, good effectiveness.
MAT	5	RIGHT LEG	Really liked it, easy to apply, did well.
MAT	10	LEFT ARM	NO COMMENTS
MAT	10	LEFT LEG	No problems whatsoever. The C clamp goes on very quick and very simple.
MAT	10	RIGHT ARM	Easy to apply one handed, tightened quickly.
MAT	10	RIGHT LEG	NO COMMENTS
MAT	8	LEFT ARM	Occluded blood flow, but pinched skin.
MAT	8	LEFT LEG	NO COMMENTS
MAT	8	RIGHT ARM	It hurts a lot.
MAT	8	RIGHT LEG	Didn't seem to have a problem. I felt I was able to stop the blood flow.
MAT	4	LEFT ARM	Easy to apply. Good leverage. Pinches skin.
MAT	4	LEFT LEG	Overall assessment excellent. Easy to use blindfolded. Not too many moving parts so it definitely worked and worked fast.
MAT	4	RIGHT ARM	Good tourniquet. Easy to apply. No need to maintain positive control while increasing tension.
MAT	4	RIGHT LEG	Easy to apply. Comfortable stopping point.
MAT	9	LEFT ARM	Quick application, quick results.
MAT	9	LEFT LEG	Was pretty easy to use blindfolded, and application worked very quickly, and cut off blood supply very quickly.
MAT	9	RIGHT ARM	Works quickly.
MAT	9	RIGHT LEG	Went on quickly, cut off circulation quickly, works well.
MAT	3	LEFT ARM	Easy to use, easy to put on.
MAT	3	LEFT LEG	Easy to use. No problems.
MAT	3	RIGHT ARM	The only problem I had was the strap slipped through the buckle.
MAT	3	RIGHT LEG	Easy application.
MAT	1	LEFT ARM	Quick and easy to get torque on. No problems.
MAT	1	LEFT LEG	It was very quick and easy to apply. Good torque and cinches down very quick.
MAT	1	RIGHT ARM	Easy application, easy to cinch down.
MAT	1	RIGHT LEG	Very easy to apply and very quick to cinch down and received good torque on the dial.
MAT	7	LEFT ARM	Found it very easy to use and very easy to apply enough torque.
MAT	7	LEFT LEG	No problems. Difficult to secure.
MAT	7	RIGHT ARM	NO COMMENTS

TOURNIQUET	SUBJECT	EXTREMITY	COMMENTS
MAT	7	RIGHT LEG	Went on easily, no problems at all.
OHT	2	LEFT ARM	Application was easier. It didn't feel like it was on that tight, but I was able to restrict blood flow.
OHT	2	RIGHT LEG	The application was pretty easy. I was able to get it on with no problems, and even though I was cranking it down pretty hard, the guys still felt a pulse.
OHT	2	LEFT LEG	Went on easy, but straps were confusing. Felt tight, but didn't restrict blood flow.
OHT	6	LEFT ARM	Easy to apply, but with one hand can't get enough torque to restrict blood flow.
OHT	6	RIGHT LEG	Easy to use. Tightened quickly.
OHT	5	RIGHT LEG	Easy to use.
OHT	10	LEFT ARM	I felt it was simple to use and pretty quick.
OHT	10	RIGHT ARM	Difficult to tighten, easy to apply.
OHT	8	LEFT ARM	NO COMMENTS
OHT	8	LEFT LEG	NO COMMENTS
OHT	8	RIGHT ARM	It was extremely difficult to apply especially since I couldn't see.
OHT	8	RIGHT LEG	It was confusing and hard to put o
OHT	4	LEFT ARM	Easy to apply, however straps got twisted and were too low on my arm. Blood flow not occluded.
OHT	4	RIGHT LEG	Thought the application was good. Easy to use. Didn't really matter if you dropped it, it doesn't snap back. Overall a good rating.
OHT	9	LEFT ARM	Once again got it on right, got it on quickly, but couldn't cinch it down tight enough.
OHT	9	RIGHT LEG	Seemed to be simple enough, got it on very easily but couldn't get it tight enough to cut off blood supply. Possibly because I'm a bigger guy and my thighs are pretty big, I gave it max effort and it didn't work.
OHT	3	LEFT ARM	Unsatisfactory. Couldn't get enough pull to stop blood flow.
OHT	3	RIGHT LEG	Easy to apply, but had difficulties tightening it down.
OHT	1	LEFT ARM	It seemed to cinch down quickly, but upon trying to tighten it the Velcro holder on the tourniquet got blocked into the buckle and was very difficult to tighten the opposite end.
OHT	1	RIGHT ARM	Difficult to cinch down tight. Difficult to know which strap is what.
OHT	7	LEFT ARM	I like the 2" better, it's easier to grip and easier to torque down on.
OHT	7	LEFT LEG	Easy to apply, but difficult to winch down.
OHT	7	RIGHT ARM	Application was very easy.
OHT	7	RIGHT LEG	Very difficult to get tight enough. Very difficult to torque down.
OHT2	2	RIGHT ARM	Application was easy. Able to achieve restriction.

TOURNIQUET	SUBJECT	EXTREMITY	COMMENTS
OHT2	6	LEFT LEG	Application was fairly easy. It was difficult to cinch down and didn't occlude blood flow.
OHT2	6	RIGHT ARM	Easy to apply, stopped blood flow quickly.
OHT2	5	LEFT ARM	Awkward application, hard to use.
OHT2	5	LEFT LEG	Easy to use, Easy to apply.
OHT2	5	RIGHT ARM	I had difficulty getting it tight.
OHT2	10	LEFT LEG	Application quick. Not enough torque.
OHT2	10	RIGHT LEG	It went on very easy and was very easy to cinch up.
OHT2	4	LEFT LEG	Easy to use. Presence of being wet and sandy had little effect on my operation of it. I give it a good rating.
OHT2	4	RIGHT ARM	Application was easy, completed in 17 seconds.
OHT2	9	LEFT LEG	Got it on very easily. Easier to use the larger model but no matter how hard I cranked down it didn't work. It made a ripping sound, so I had to switch to the other.
OHT2	9	RIGHT ARM	Easy application.
OHT2	3	LEFT LEG	Easy application
OHT2	3	RIGHT ARM	Clip on the tourniquet got jammed up and took me a while to tighten it, and I didn't feel any results.
OHT2	1	LEFT LEG	Works easily. Cinch straps down at beginning to get device to function properly.
OHT2	1	RIGHT LEG	It was difficult to determine which strap goes around the appendage and which strap is used to cinch it down. Once it was on it was a simple mechanism.
QUICK	2	LEFT ARM	Application is easy, however I was able to turn the knob, but no progress.
QUICK	2	LEFT LEG	Application was very easy, however tightening it down proved to be a challenge. I wasn't able to get it tight enough to restrict blood flow no matter how much I tugged on it and turning the knob, it just wasn't budging. It is just a zip tie, but I think the sand had something to do with it.
QUICK	2	RIGHT ARM	Couldn't turn the knob.
QUICK	2	RIGHT LEG	Putting it on was pretty easy, and once again I wasn't able to tighten it up. I couldn't turn the knob. The sand interfered a lot.
QUICK	6	LEFT ARM	Application was easy but I couldn't tighten far enough because of leverage on the mechanism and the chain got caught.
QUICK	6	LEFT LEG	Tourniquet broke.
QUICK	6	RIGHT ARM	Tourniquet was bound up and stripped out.
QUICK	6	RIGHT LEG	Tourniquet was easy to apply, but couldn't be tightened down far enough because the wrenching mechanism wasn't big enough.
QUICK	5	LEFT ARM	Hard to operate. Couldn't get the Velcro off to even get it over my arm, and could not pull the zip tight, had to use the winder the whole way. I didn't like it.
QUICK	5	LEFT LEG	Easy to apply, hard to tighten.

TOURNIQUET	SUBJECT	EXTREMITY	COMMENTS
QUICK	5	RIGHT ARM	Can't get it to tighten up.
QUICK	5	RIGHT LEG	Had trouble tightening it, and the locking mechanism failed and would not secure.
QUICK	10	LEFT ARM	Easy to slide arm through it, but to actually get it tight was difficult and you had to spin it with the knob for long way so it took a little while, and there was not enough torque.
QUICK	10	LEFT LEG	Application easy, but tightening mechanism is too small.
QUICK	10	RIGHT ARM	I couldn't get it to tighten up, it was too slippery in my hands, and to crank it down, the sand was in it, I couldn't get one turn.
QUICK	10	RIGHT LEG	Application quick. Not enough torque.
QUICK	8	LEFT ARM	It was extremely difficult to crank down to where I felt it would cut off blood flow.
QUICK	8	LEFT LEG	Couldn't get it tight enough.
QUICK	8	RIGHT ARM	NO COMMENTS
QUICK	8	RIGHT LEG	Couldn't get it tight enough, didn't have enough leverage.
QUICK	4	LEFT ARM	Applied with right hand while blindfolded. Biggest complaint is the mechanism used to increase the torque wasn't quite big enough to get leverage.
QUICK	4	LEFT LEG	Sand in the mechanism is a problem. Thumbscrew doesn't allow enough torque to restrict blood flow.
QUICK	4	RIGHT ARM	Sand reduces the effectiveness and ease of use. Turning mechanism is too small.
QUICK	4	RIGHT LEG	Again, any sand in the mechanism makes it extremely difficult to operate. Difficult to open enough to get over my leg due to the sand in mechanism. The size of the knob, which you rotate to increase tension, could be bigger to give more leverage. I did have the foresight to bang the unit out to free the sand and debris.
QUICK	9	LEFT LEG	Couldn't get it to tighten.
QUICK	9	LEFT ARM	Sand gets caught in the turning mechanism and it's difficult to tighten. Even after removing the turning mechanism, it didn't function.
QUICK	9	RIGHT ARM	I managed to tap the sand out of the mechanism to make it work.
QUICK	9	RIGHT LEG	Got it on fine, but had to bang the sand out to get it to work. The turning mechanism is too small to get it tight enough.
QUICK	3	LEFT ARM	The turn buckle jammed on me, I got it tightened but it took a while get it through the sand.
QUICK	3	LEFT LEG	Hard to turn.
QUICK	3	RIGHT ARM	Easy to apply, hard to cinch down.
QUICK	3	RIGHT LEG	Couldn't get enough hamstrings on the turnbuckle.

TOURNIQUET	SUBJECT	EXTREMITY	COMMENTS
QUICK	1	LEFT ARM	It was very difficult to cinch the device down initially without using the turning device. Once the turning device is engaged due to sand apparently in the gears, it's had to get any torque.
QUICK	1	LEFT LEG	Gears stripped out.
QUICK	1	RIGHT ARM	I was unable to cinch it down due to sand in mechanism. Gears stripped immediately upon torqueing down and never got any tightness around the arm.
QUICK	1	RIGHT LEG	Easy to install. Difficult to get much torque. Handle too small.
QUICK	7	LEFT ARM	Got three clicks before it froze up, complete failure.
QUICK	7	RIGHT ARM	Easy application. Gears stripped out.
QUICK	7	LEFT LEG	Found it very easy to get on, but problems due to sand in the keeper getting caught in the mechanism caused difficulty in tightening down.
QUICK	7	RIGHT LEG	I wound the winding mechanism as far as I could, then the release mechanism malfunctioned and had to be cut off.
TK	2	LEFT ARM	Easy application. No problems.
TK	2	LEFT LEG	Putting it on was super easy. I used both hands and was able to restrict blood flow with no problems.
TK	2	RIGHT ARM	It seemed pretty easy, application was pretty basic. The only difficulty is I couldn't really tell when it was hooked. I had to tug on it a couple of times.
TK	2	RIGHT LEG	Easier with two hands.
TK	6	LEFT ARM	Application quick and easy.
TK	6	LEFT LEG	Application was quick and easy.
TK	6	RIGHT ARM	It was pretty easy to put on, the only problem I had was attaching at the end, but it stopped blood flow.
TK	6	RIGHT LEG	Application was easy and quick.
TK	5	LEFT ARM	I like it; it's a good one except for securing at the end.
TK	5	LEFT LEG	Applied to left thigh, it was quick and easy, but only hard part was securing it under itself with it being so tight.
TK	5	RIGHT ARM	Easy, liked it. No problems.
TK	5	RIGHT LEG	Broke.
TK	10	LEFT ARM	Application quick and easy, hard to secure.
TK	10	LEFT LEG	Two handed application very easy.
TK	10	RIGHT ARM	Had a little difficulty getting it started using the hook and securing was a problem. It was still very quick.
TK	10	RIGHT LEG	Easy with use of two hands.
TK	8	LEFT ARM	Went on easy except at the end, securing to itself was really hard.
TK	8	LEFT LEG	I thought it was very easy to put on.
TK	8	RIGHT ARM	NO COMMENTS

TOURNIQUET	SUBJECT	EXTREMITY	COMMENTS
TK	8	RIGHT LEG	NO COMMENTS
TK	4	LEFT ARM	Initial thoughts, when wet it was difficult to maintain positive control of the latex rubber. If you lose control, it whips back around and could hit you in the face. Not too difficult to apply but one of the major problems is getting the S hook under the latex with camis on and it being wet.
TK	4	LEFT LEG	NO COMMENTS
TK	4	RIGHT ARM	Found it to be user friendly. The only problem that I see with it is without the aid of sight, after a couple of turns, it is difficult to get the hook underneath one of the wraps in order to fasten and if you lose positive control, it will snap back and you have to start all over.
TK	4	RIGHT LEG	Aid of two hands is easier. S hook is quick and efficient.
TK	9	LEFT ARM	NO COMMENTS
TK	9	LEFT LEG	Easy application, quick results, easy to secure.
TK	9	RIGHT ARM	Application was very easy. Not a lot of moving parts so it worked and worked fast. The only problem is finding a way to secure.
TK	9	RIGHT LEG	Easiest one yet, especially with two hands.
TK	3	LEFT ARM	Easy to apply, no problems.
TK	3	LEFT LEG	It did pretty good, but it broke while I was applying the hook.
TK	3	RIGHT ARM	No problems.
TK	3	RIGHT LEG	No problems, hurt like hell.
TK	1	LEFT ARM	Awkward application, hard to use.
TK	1	LEFT LEG	NO COMMENTS
TK	1	RIGHT ARM	It was quick and relatively simple and easy to get a tight fit.
TK	1	RIGHT LEG	No problems. Difficult to secure.
TK	7	LEFT ARM	Easy to apply, difficult to secure.
TK	7	LEFT LEG	It was very easy to use and very effective in my opinion.
TK	7	RIGHT ARM	Easy to apply, but difficult to secure.
TK	7	RIGHT LEG	Easy to apply, difficult to secure.

APPENDIX D

APPLICATION TIMES

APPLICATION TIMES (SECONDS): Forearms

Extremity = Right Forearm

Subject	CAT	MAT	OHT1	OHT2	QUICK	TK
1	131	48	165		[M]	50
2	110	82		51	[M]	110
3	99	68		88	93	72
4	93	34		17	38	115
5	88	56		102	[M]	51
6	108	[M]		52	[M]	46
7	204	[M]		59	65	84
8	197	127		[A]	79	110
9	69	39		29	65	67
10	83	36	57		[M]	60

Mean	118.20	61.25	111.00	56.86	68.00	76.50
Std Dev	46.53	31.34	76.37	30.10	20.40	26.77
n	10	8	2	7	5	10

[A] application failure, [M] mechanical failure

Extremity = Left Forearm

Subject	CAT	MAT	OHT1	OHT2	QUICK	TK
1	72	66	187		112	60
2	120	111		51	[M]	80
3	135	91	47		77	65
4	71	50	25		49	64
5	83	82		68	85	56
6	91	33	84		69	47
7	186	35		44	[M]	107
8	69	61		60	72	119
9	71	44	48		46	67
10	61	27	59		56	84

Mean	95.90	60.00	75.00	55.75	70.75	74.90
Std Dev	39.68	27.65	58.13	10.47	21.55	22.90
n	10	10	6	4	8	10

[A] application failure, [M] mechanical failure

APPLICATION TIMES (SECONDS): Legs

Extremity = Right Leg

Subject	CAT	MAT	OHT1	OHT2	QUICK	TK
1	84	45		86	99	34
2	75	46	37		[M]	29
3	38	50	65		45	43
4	45	30	26		75	20
5	68	30	58		[M]	[M]
6	38	59		48	39	25
7	43	36	51		25	52
8	68	56	147		121	68
9	55	31	29		43	28
10	72	29		40	105	72

Mean	58.60	41.20	59.00	58.00	69.00	41.22
Std Dev	16.87	11.46	41.47	24.58	35.90	18.95
n	10	10	7	3	8	9

[A] application failure, [M] mechanical failure

Extremity = Left Leg

Subject	CAT	MAT	OHT1	OHT2	QUICK	TK
1	53	33		46	[M]	43
2	[M]	40	74		189	37
3	46	30		42	[M]	38
4	35	44		27	34	29
5	51	86		36	55	35
6	40	31		40	[M]	40
7	35	33	55		71	34
8	81	57		50	92	67
9	49	30		24	43	37
10	75	31		89	110	38

Mean	51.67	41.50	64.50	44.25	84.86	39.80
Std Dev	16.35	17.82	13.44	20.13	53.15	10.25
n	9	10	2	8	7	10

[A] application failure, [M] mechanical failure

APPENDIX E

PERCENTAGE OF ARTERIAL OCCLUSION

PERCENTAGE OF ARTERIAL OCCLUSION: Forearms

Extremity = Right Forearm

Subject	CAT	MAT	OHT1	OHT2	QUICK	TK
1	–30.85	76.68	–143.68		M	53.63
2	*	94.39		91.23	M	*
3	70.59	87.91		–157.61	–109.59	88.85
4	66.78	85.63		90.39	–14.53	92.55
5	79.21	*		–352.27	M	61.61
6	77.89	M		90.74	M	*
7	–72.89	M		94.31	81.93	*
8	*	90.97		M	88.89	83.97
9	79.91	68.23		*	–85.18	62.58
10	*	81.53	–56.34		M	90.44

A application failure, M mechanical failure, * missing data

Extremity = Left Forearm

Subject	CAT	MAT	OHT1	OHT2	QUICK	TK
1	55.72	80.10	–21.13		–54.27	84.13
2	93.90	89.27		78.61	M	*
3	*	68.14	–93.87		62.76	88.40
4	75.04	90.83	–48.30		87.26	70.84
5	46.04	91.21		–29.60	–107.50	
6	88.99	38.54	-0.14		5.03	81.38
7	38.71	87.22		65.67	M	*
8	67.75	70.62		95.06	–100.99	95.96
9	79.60	69.75	–55.30		-51.29	69.58
10	20.32	47.12	–24.62		93.98	68.96

A application failure, M mechanical failure, * missing data

PERCENTAGE OF ARTERIAL OCCLUSION: Legs

Extremity = Right Leg

Subject	CAT	MAT	OHT1	OHT2	QUICK	TK
1	85.40	82.14		61.53	–42.64	71.58
2	87.56	61.31	–35.15		M	80.51
3	91.81	98.19	64.69		57.19	27.86
4	90.05	92.89	–41.77		–5.53	52.71
5	86.76	–73.04	–27.15		M	M
6	88.02	94.52		83.89	10.83	90.62
7	94.37	90.14	–6.19		10.58	48.68
8	94.54	*	10.26		–114.17	95.28
9	82.57	82.32	30.96		–28.00	*
10	72.56	72.78		83.13	6.57	88.70

A application failure, M mechanical failure, * missing data

Extremity = Left Leg

Subject	CAT	MAT	OHT1	OHT2	QUICK	TK
1	87.16	85.82		90.27	M	91.25
2	A	95.35	–58.37		5.55	*
3	91.06	92.76		78.41	M	39.59
4	83.68	51.77		73.54	–11.69	–211.08
5	71.83	–84.93		93.19	-8.98	66.37
6	86.04	*		94.85	M	91.39
7	92.71	64.17	–1.47		–5.10	83.11
8	90.96	76.24		60.88	1.76	51.37
9	84.50	83.61		16.87	–13.72	71.22
10	85.06	55.92		53.80	11.13	*

A application failure, M mechanical failure, * missing data

APPENDIX F

PRELIMINARY ANALYSIS OF INCREASES IN ARTERIAL BLOOD FLOW WITH INCOMPLETE TOURNIQUET APPLICATION

INTRODUCTION

The efficacies of the tourniquets in occluding arterial inflow varied widely across limbs tested and tourniquet designs. Although calculated impedance blood flows after tourniquets were applied tended to be decreased with Doppler No-flow outcomes and present with Doppler Flow outcomes, impedance blood flows were more sensitive than the Doppler indications of blood flow. Indeed, impedance blood flow was *increased* in a relatively large number of trials in which tourniquet applications failed to result in a Doppler No-flow call. These seemingly counterintuitive observations cannot be fully explained by the tourniquet trial results alone.

Preliminary/exploratory occlusion tests were conducted at New York Medical College to confirm and further characterize the increased segmental blood flow that appeared to accompany incomplete tourniquet application.

METHODS

Two controlled tests were completed to investigate increases in forearm blood flow that might be produced by only partial arterial occlusion of the upper arm:

1. A standard blood pressure cuff was slowly inflated on the upper arm of a test subject at a rate of 1 mmHg/s until a maximum pressure of 200 mmHg was reached and the cuff was then deflated at the same rate.

2. One of the test tourniquets (MAT) was used on the same subject's arm over the approximate same time period until full occlusion was observed in the recorded physiologic variables. The tourniquet was then released and recordings were continued during a postocclusion recovery period.

Continuous forearm IPG and EKG recordings were made during both runs with the same instrumentation used in the tourniquet trials. In addition, a finger blood pressure unit (Finometer; Finapres Medical Systems BV) was used to record the distal index finger's blood pressure (BP) continuously during both tests. Both tests were conducted on a 66 yo male subject in the supine position wearing gym shorts and a T shirt.

RESULTS: BLOOD PRESSURE CUFF

The subject's blood pressure before initiating occlusion was 134/85 mmHg. Figures F2–F9 show the subject's finger BP, EKG, and forearm impedance ΔR waveform recorded at various cuff inflation pressures during the test sequence. Pulse amplitudes of both the impedance ΔR and the finger BP recordings were elevated when the cuff was initially placed on the upper arm and inflated to between approximately 20 and 80 mmHg. At a cuff inflation pressure of approximately 140 mmHg, the ΔR pulse waveforms were reduced but remained present, while finger BP pulses had completely disappeared.

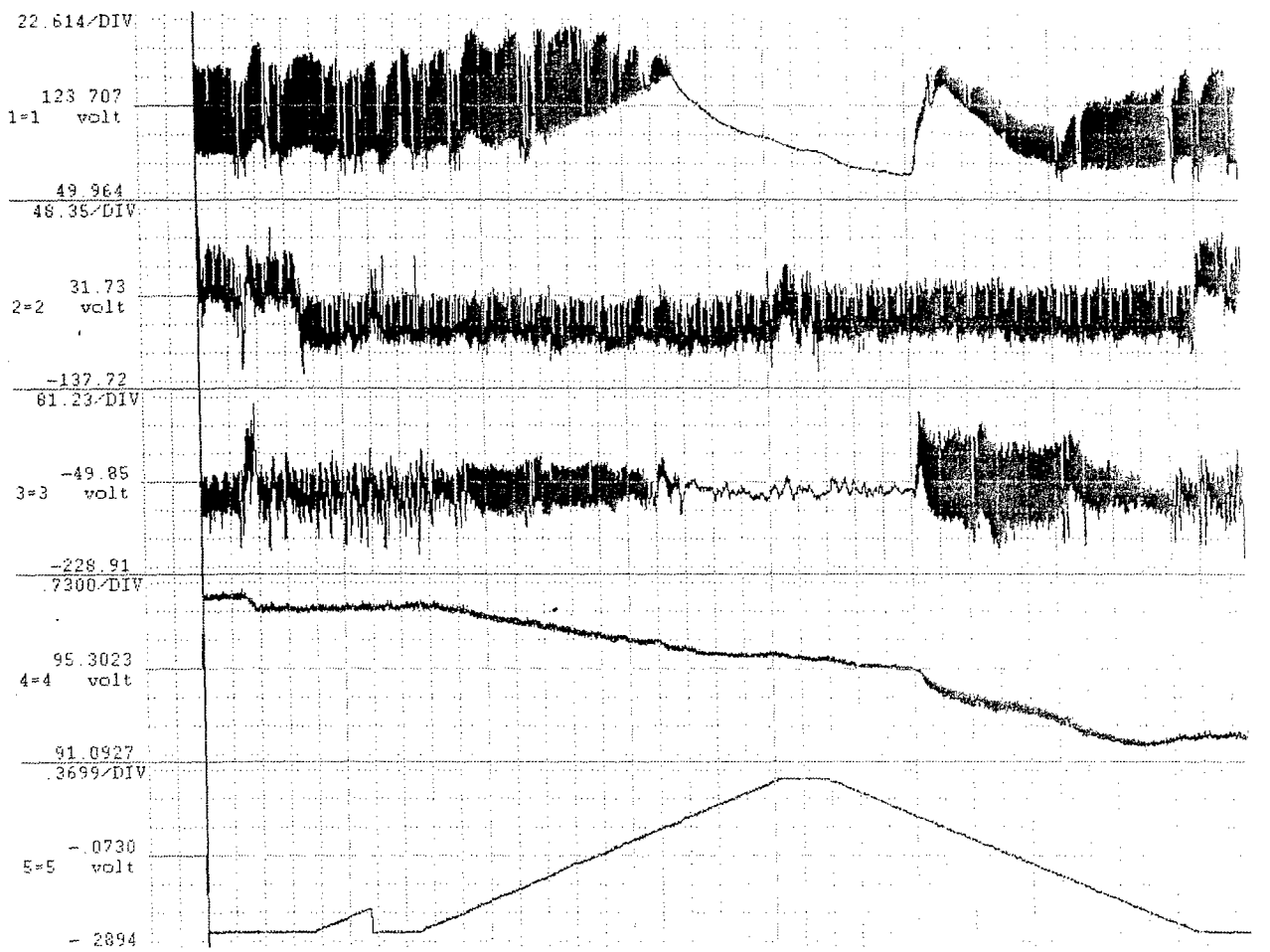

Figure F1. Compressed WinDaq recording of the blood pressure cuff test sequence. The five traces from top to bottom show finger blood pressure, EKG, Ro, ΔR, and cuff inflation pressure.

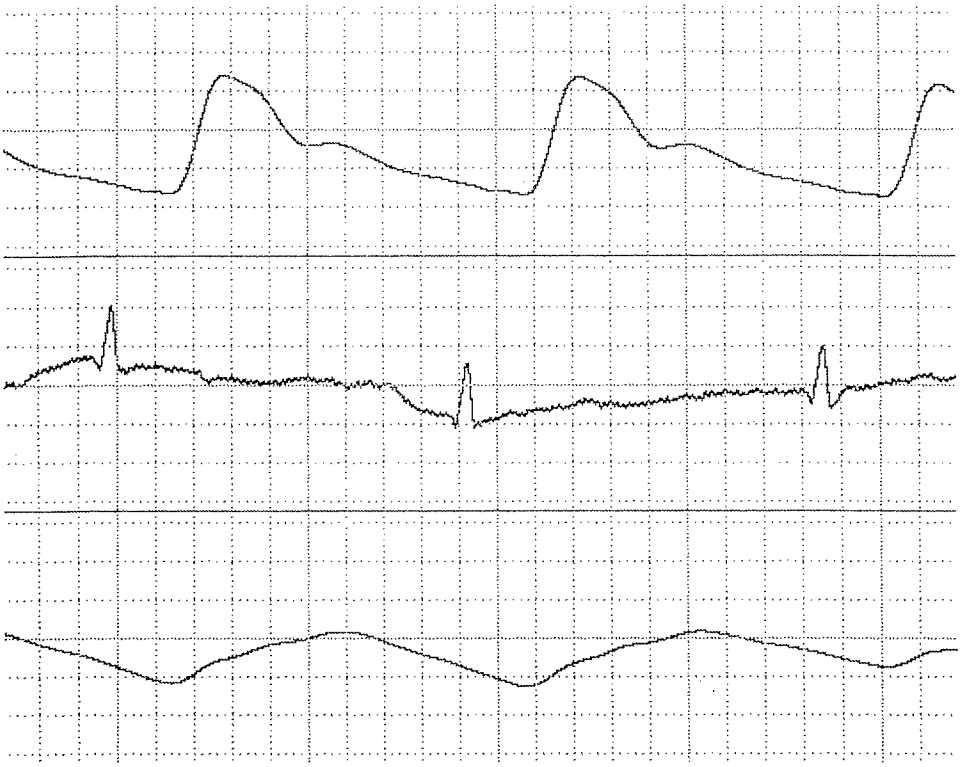

Figure F2. Finger blood pressure (top), EKG (middle), and forearm IPG ΔR (bottom) traces before cuff inflation.

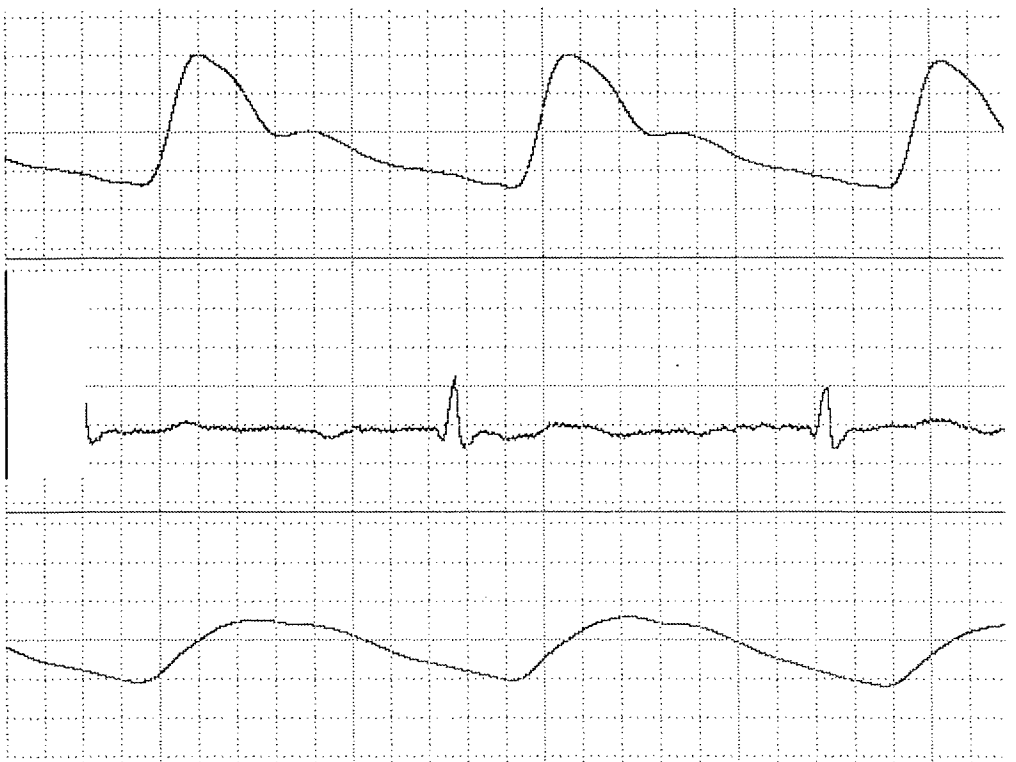

Figure F3. Finger blood pressure (top), EKG (middle), and forearm IPG ΔR (bottom) traces at 40 mmHg cuff inflation pressure.

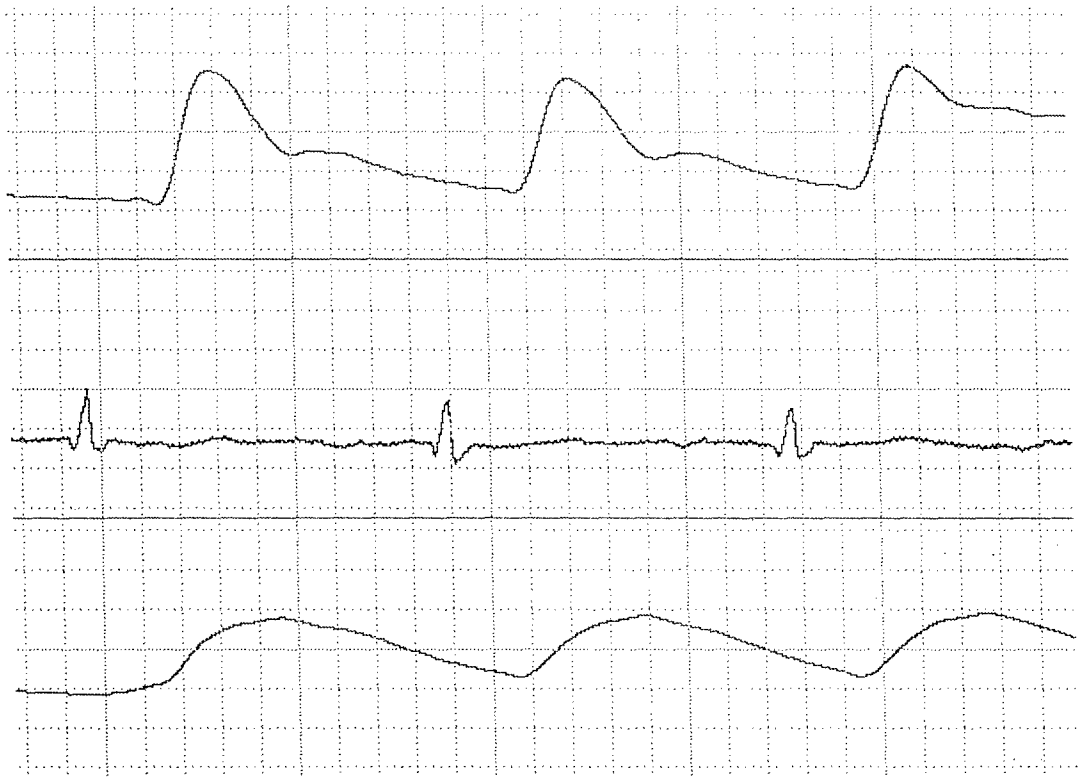

Figure F4. Finger blood pressure (top), EKG (middle), and forearm IPG ΔR (bottom) traces at 60 mmHg cuff inflation pressure.

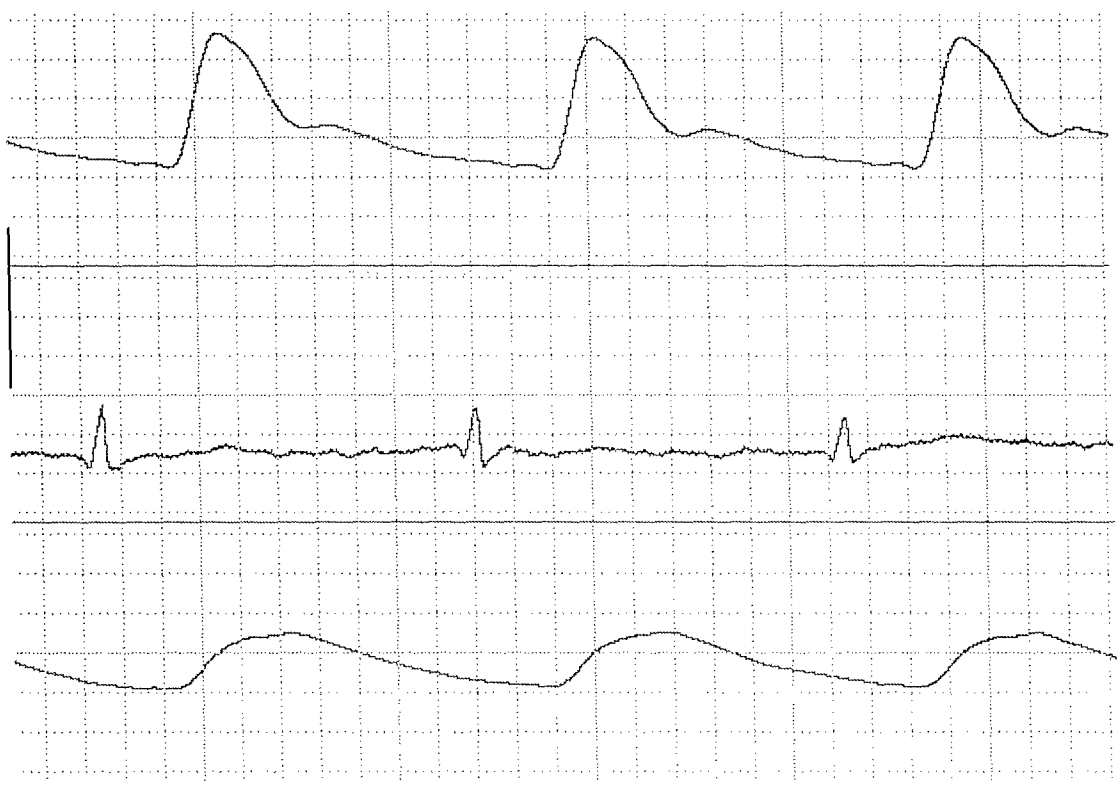

Figure F5. Finger blood pressure (top), EKG (middle), and IPG forearm blood flow (bottom) traces at 80 mmHg cuff inflation pressure.

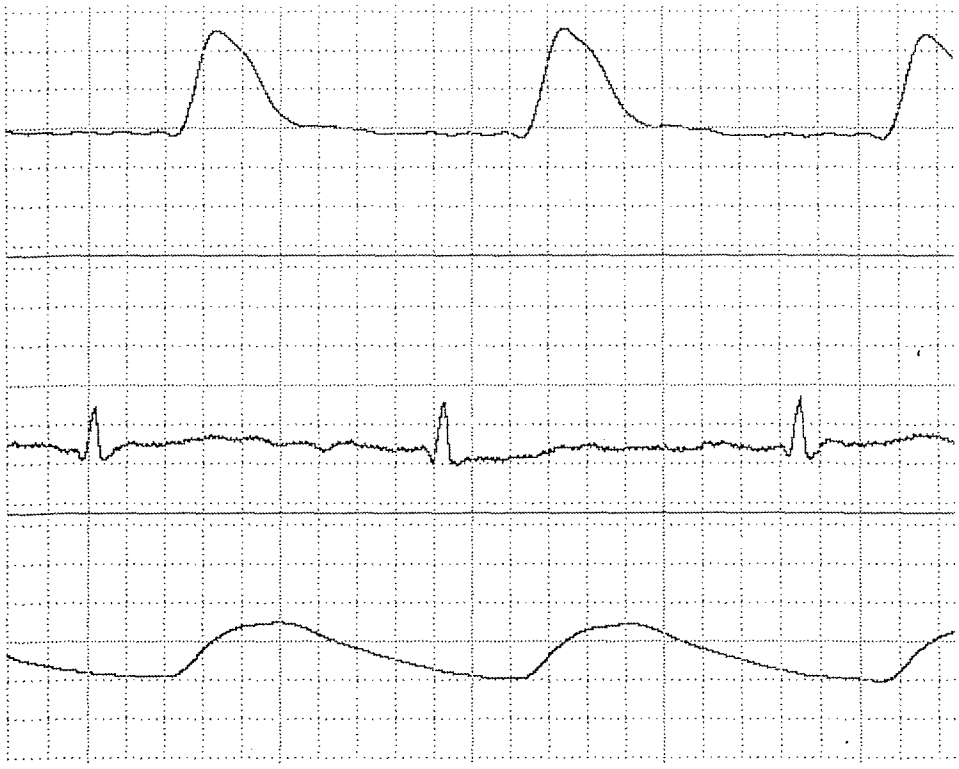

Figure F6. Finger blood pressure (top), EKG (middle), and forearm IPG ΔR (bottom) traces at 100 mmHg cuff inflation pressure.

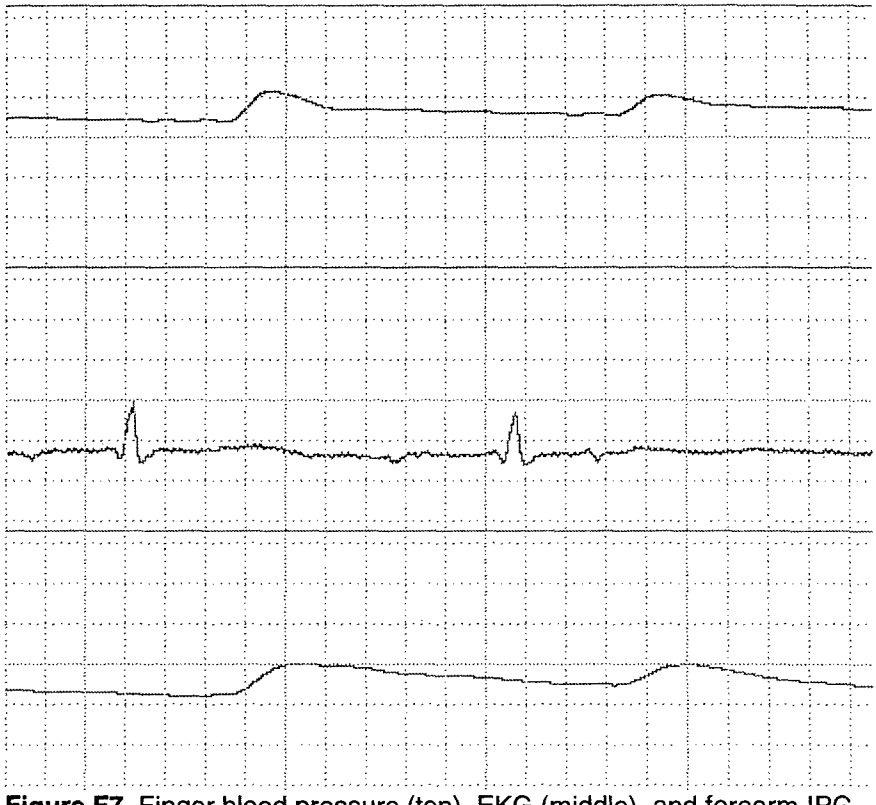

Figure F7. Finger blood pressure (top), EKG (middle), and forearm IPG ΔR (bottom) traces at 120 mmHg cuff inflation pressure.

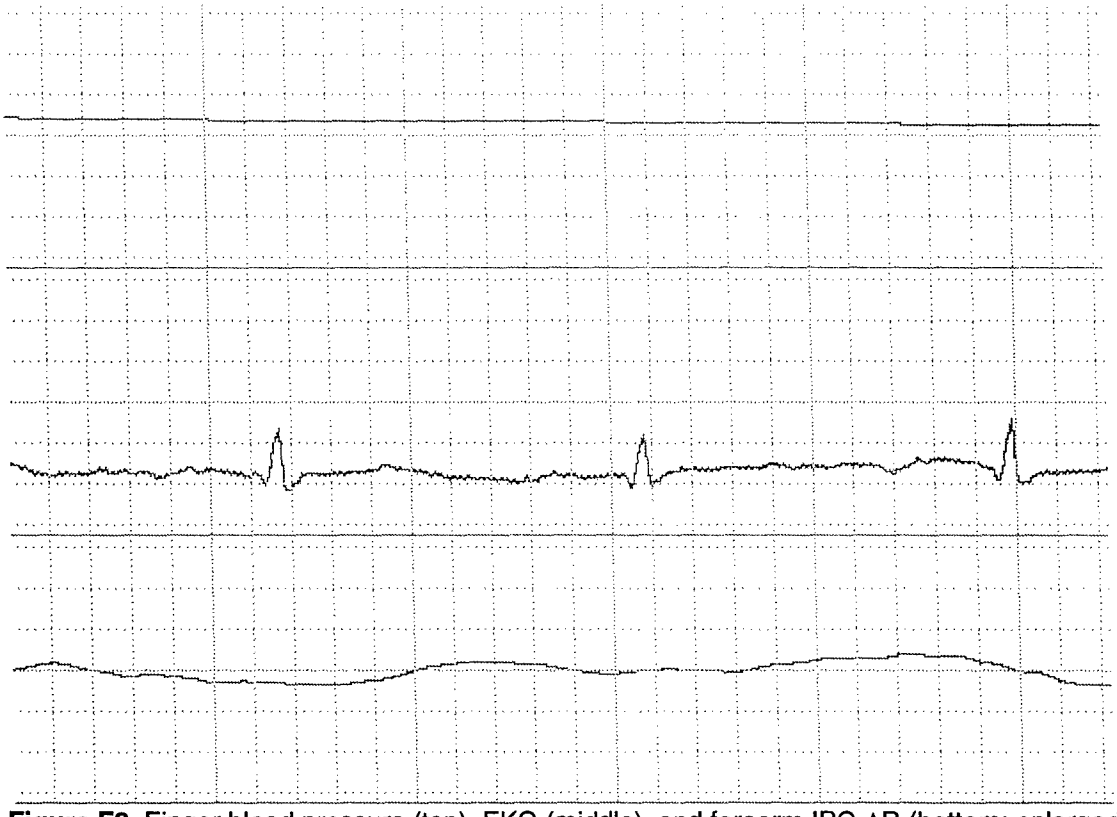

Figure F8. Finger blood pressure (top), EKG (middle), and forearm IPG ΔR (bottom; enlarged 4x) traces at 140 mmHg cuff inflation pressure.

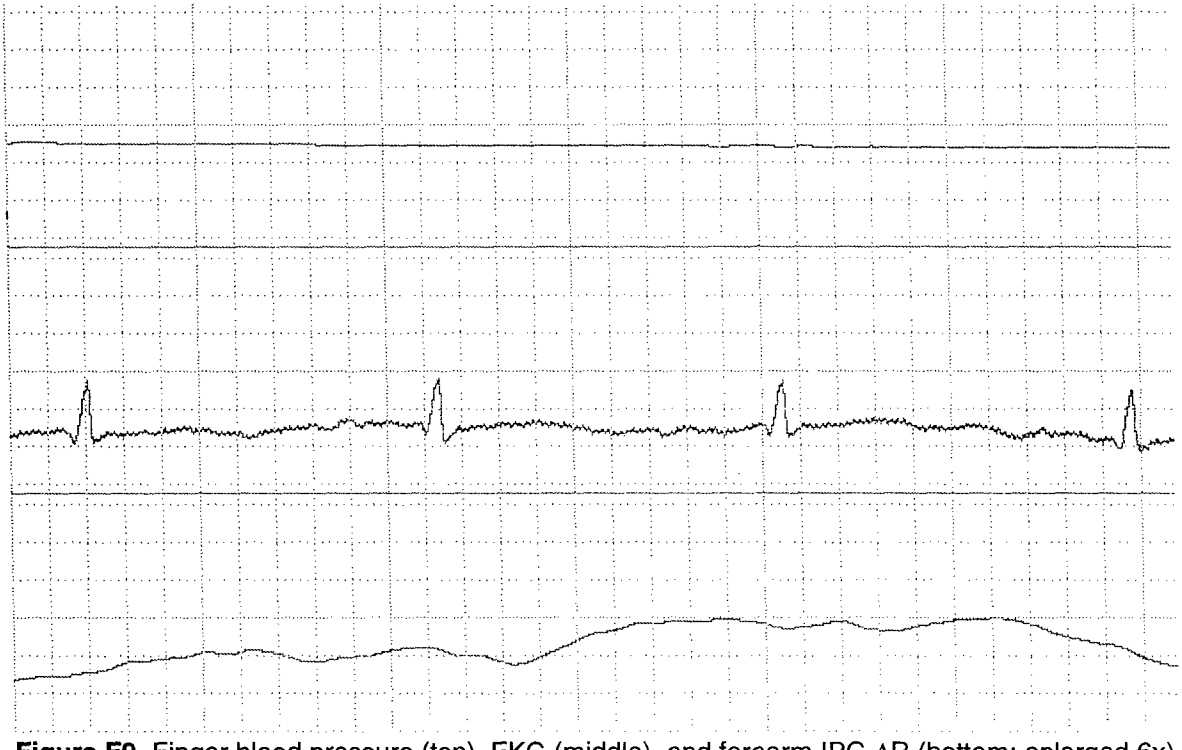

Figure F9. Finger blood pressure (top), EKG (middle), and forearm IPG ΔR (bottom; enlarged 6x) traces at 140 mmHg cuff inflation pressure.

Figure F10 shows that the forearm IPG blood flow increased with initial inflation of the blood pressure cuff, and continued to increase with further cuff inflation until the cuff pressure reached a pressure approximately equal to the subject's diastolic blood pressure (75-80 mmHg). Forearm IPG blood flow then fell with continued cuff inflation until the cuff pressure reached the subject's systolic blood pressure (150 mmHg). The subject's forearm IPG blood flow quickly approached and remained near zero until the cuff inflation pressure was decreased to approximately 150 mmHg. With continued cuff deflation, a rapid reactive hyperemic increase in forearm IPG blood flow occurred until the cuff pressure reached the subject's diastolic pressure, after which forearm blood flow continuously decreased until the cuff was fully deflated.

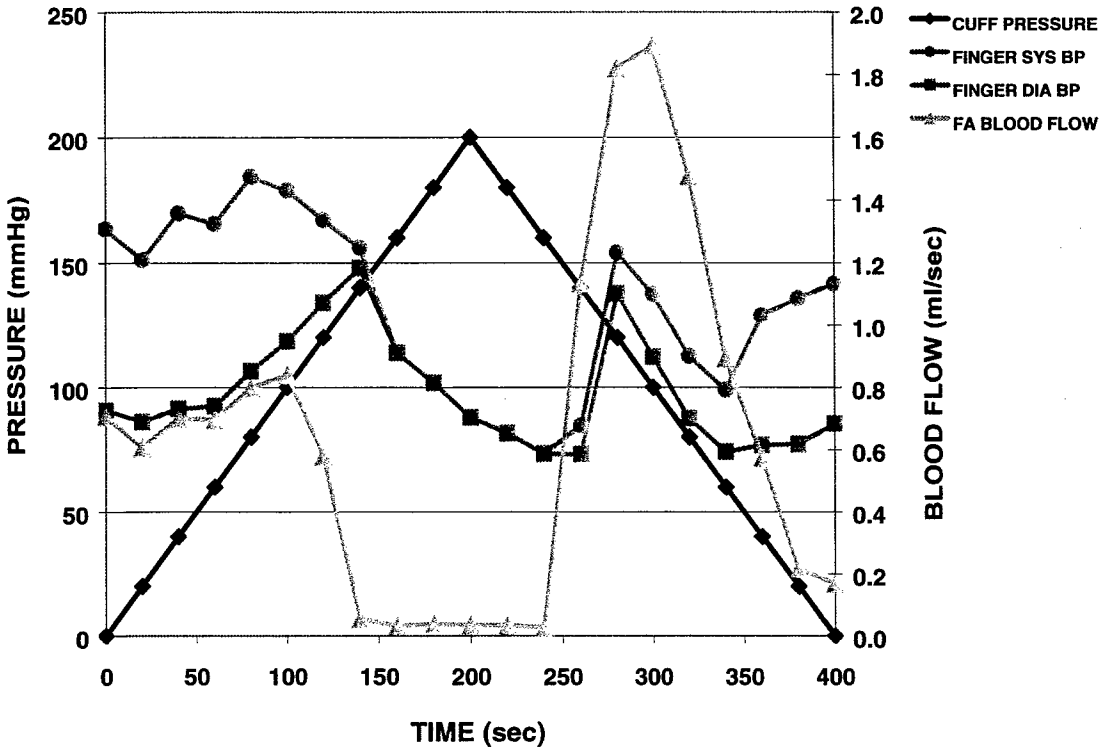

Figure F10. Cuff inflation pressure, finger systolic and diastolic blood pressures, and forearm IPG blood flow during the blood pressure cuff test sequence.

The increases in forearm IPG blood flow with initial inflation of the blood pressure cuff were consistent with changes observed in finger blood pressure and pulse pressure. Figure F10 shows that the finger diastolic blood pressure remained constant until the cuff pressure reached the diastolic pressure. During this period, finger systolic blood pressure increased approximately 25 mmHg, with a corresponding increase in the finger's pulse pressure (Figure F11). As cuff inflation pressure continued to increase above diastolic pressure, the finger pulse pressure decreased and reached zero when the cuff pressure was equal to the

finger systolic blood pressure. Pulse pressure remained zero until flow was restored with decrease of the cuff inflation pressure to levels below subject systolic pressure.

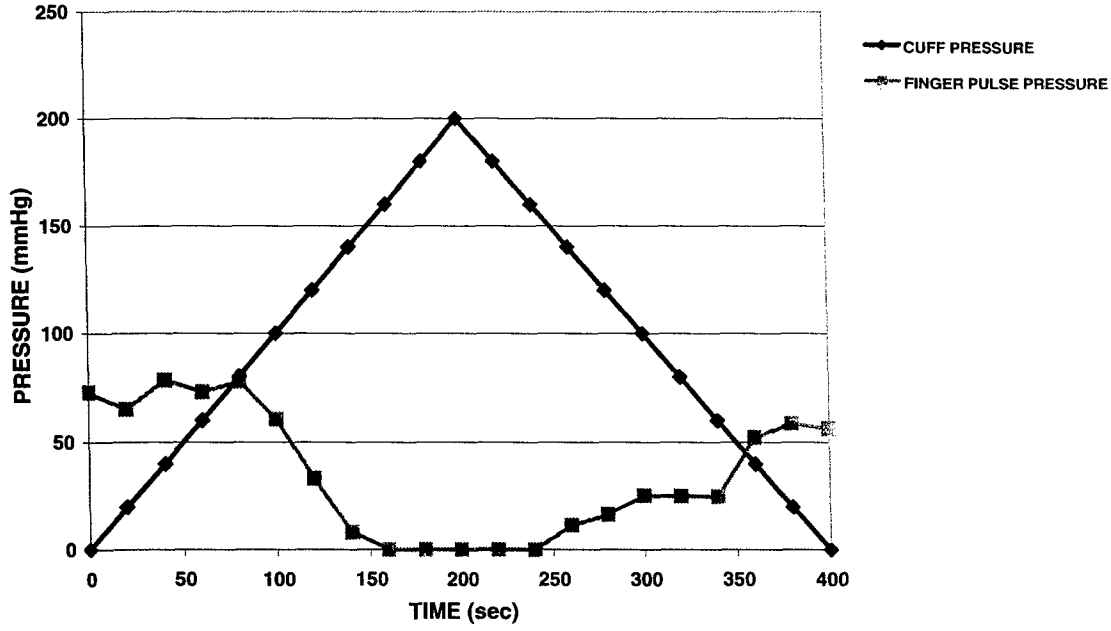

Figure F11. Cuff inflation and finger pulse pressures during blood pressure cuff test sequence.

Figure F12 shows how the values of three computed pulse properties; impedance pulse amplitude (A), total impedance pulse area (ST), and impedance pulse extrapolated pulse amplitude (EXHT); varied during the cuff inflation test sequence. These parameters reflect changes in pulse morphology that occurred on a beat-by-beat basis throughout the test, and are each independent of the subject's heart rate, which remained relatively constant (Fig. F13). Therefore any of these parameters could be used to monitor the relative changes that occur in the blood flow pulse during a given test sequence.

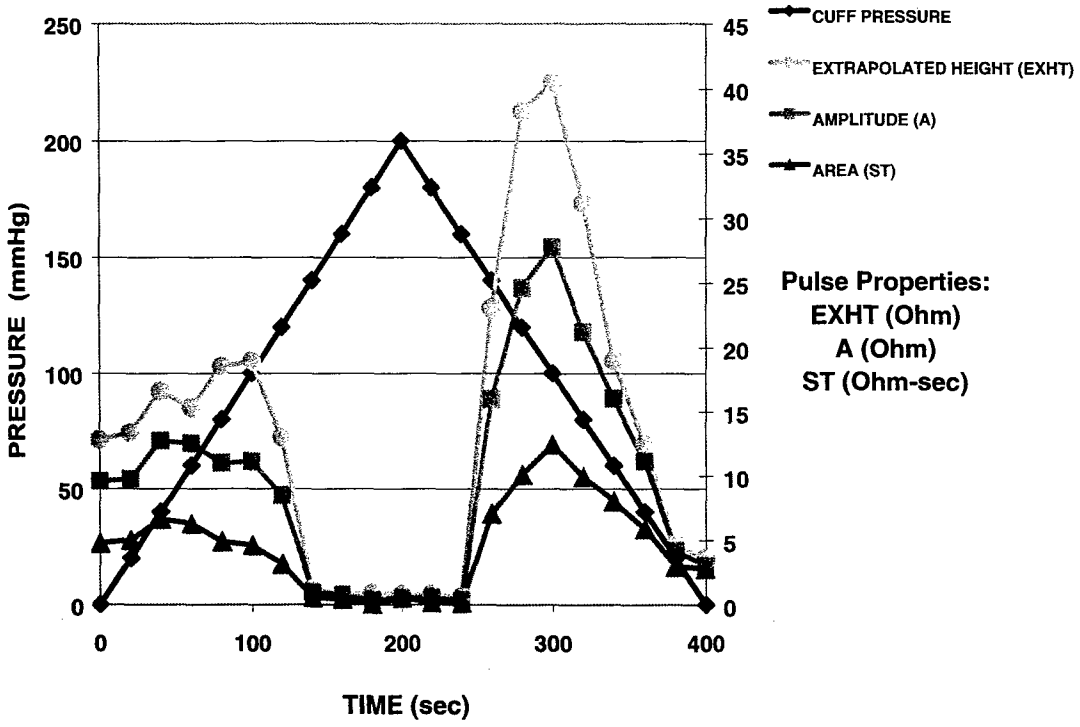

Figure F12. Cuff inflation pressure and impedance pulse properties during the blood pressure cuff test sequence.

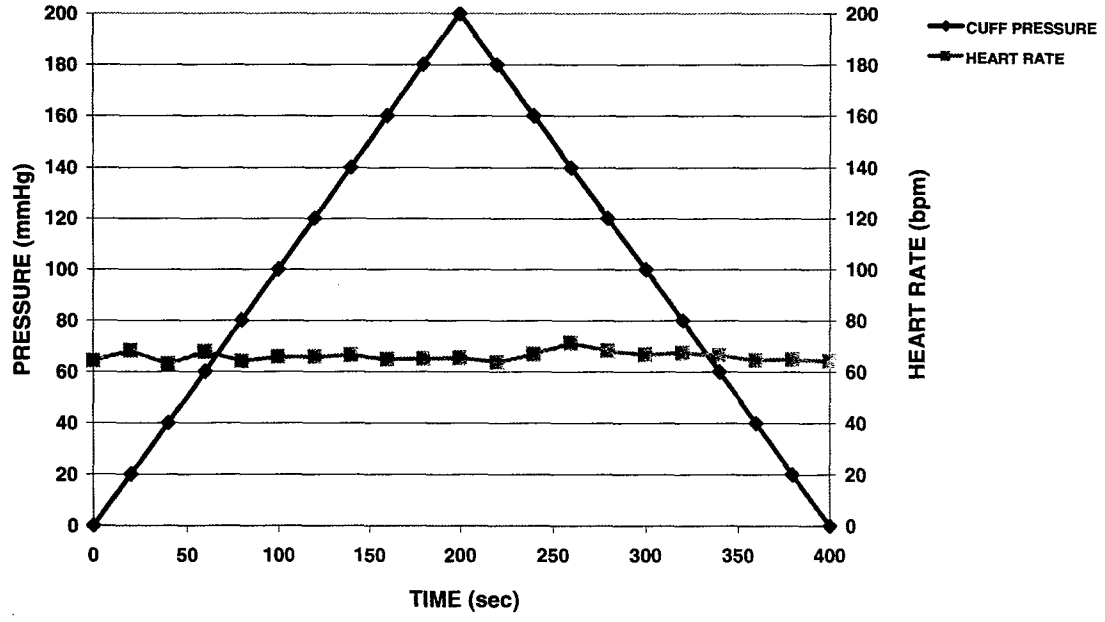

Figure F13. Cuff inflation pressure and heart rate during the blood pressure cuff test sequence.

Segmental IPG blood flow is computed with the extrapolated pulse height (EXHT), in accord with the convention established by Nyboer (1970) [See Appendix A, Eqs. (A6) and (A7). However, blood flow can also be computed with the actual IPG pulse height (A). Because the EXHT and A parameters changed in parallel during the course of this test (Figure F12), blood flows computed by either method also change in parallel (Figure F14).

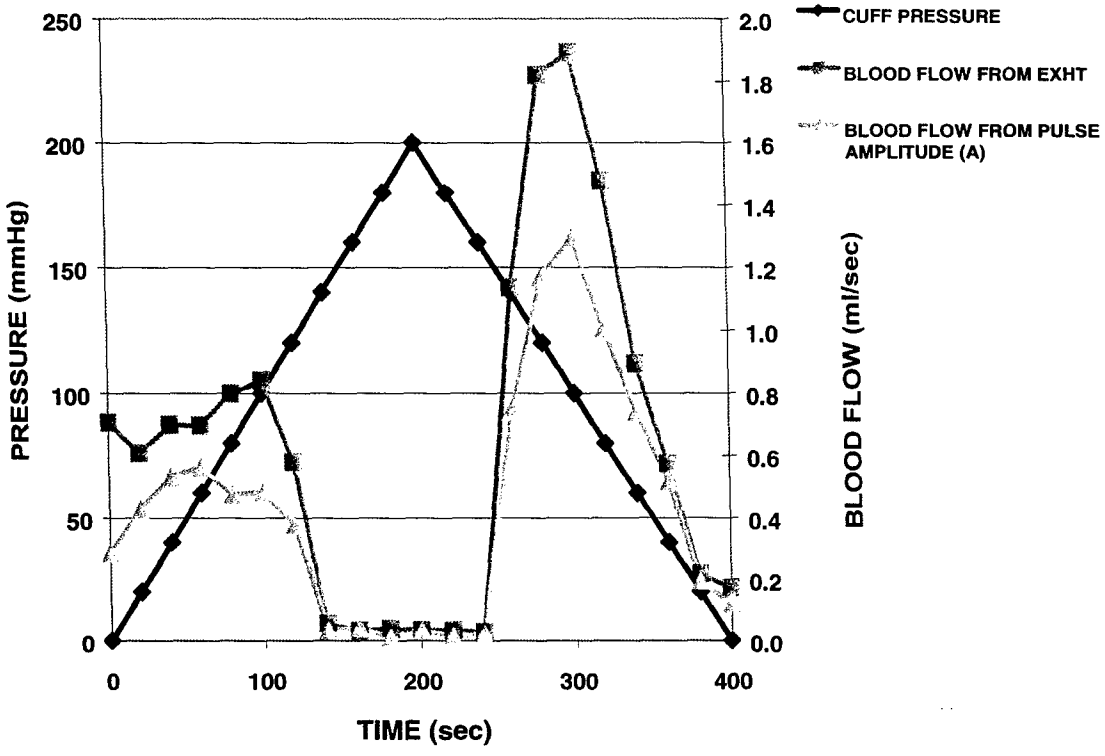

Figure F14. Cuff inflation pressure, IPG blood flow computed with EXHT, and IPG blood flow computed with pulse amplitude (A) during the blood pressure cuff test sequence.

The pulse transit time (PTT) between the heart and the impedance-sensing electrodes is an additional parameter calculated by RheoSys. This measure is independent of the method used to record pulsatile information. Any pulse detector could be used to sense the initial rise in the blood flow pulse waveform. Thus, PTT may be considered an independent measure of vascular state during the cuff test sequence. Figure F15 shows the variations in this parameter during the course of the cuff test. Note that PTT values are given for all records acquired during the test, including those taken during the period of maximum cuff inflation. Small impedance ΔR pulse waveforms were evident even during this period, from which the correspondingly small but nonzero computed blood flows indicated in Figures F10 and F12 were computed. PTT could also be determined from these waveforms.

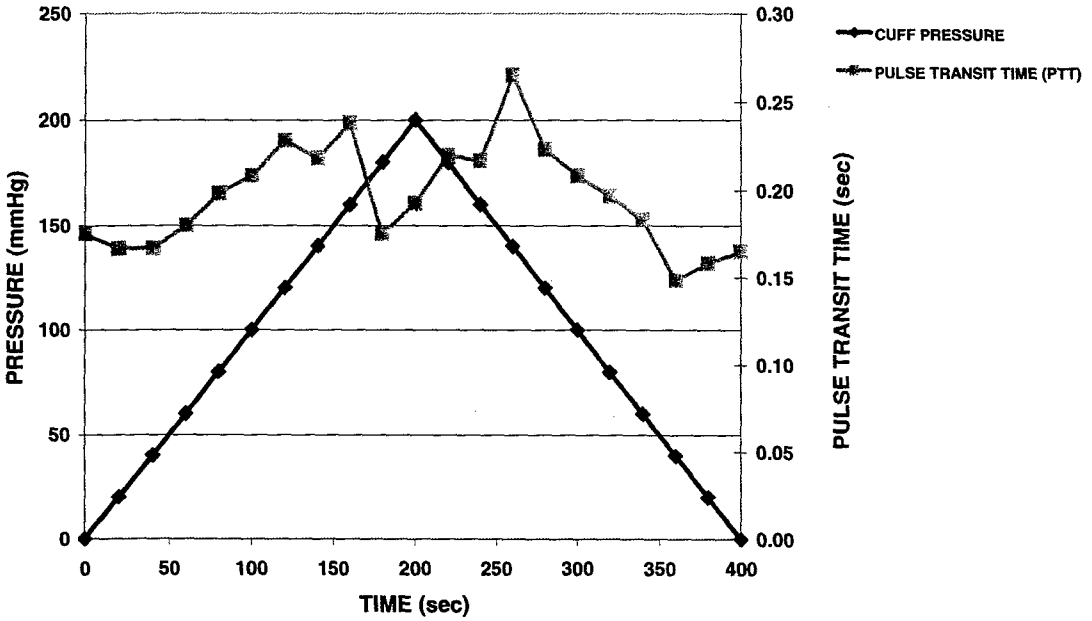

Figure F15. Cuff inflation pressure and finger pulse transition time (PTT) during the blood pressure cuff test sequence.

A rise in PTT is indicative of increased vascular compliance between the heart and the sensing location (forearm in this case), either from vasomotor dilation or other passive effects, while a decrease in PTT is a sign of decreased vascular compliance between the heart and the sensing location, either from vasoconstriction or passive effects. Figure F15 indicates that vascular compliance increased as the cuff was inflated, and decreased as the cuff was deflated.

The TIN and TOUT parameters calculated by the RheoSys program provide further insight into the vascular state of the monitored segment. TIN is the blood inflow time represented by the time period between the initial rise of the blood pulse and the occurrence of the dicrotic notch. TOUT is the blood outflow time interpreted as the period between the occurrence of the dicrotic notch and the end of the blood pulse. Figure F16 shows how these two parameters varied in the forearm throughout the cuff test sequence.

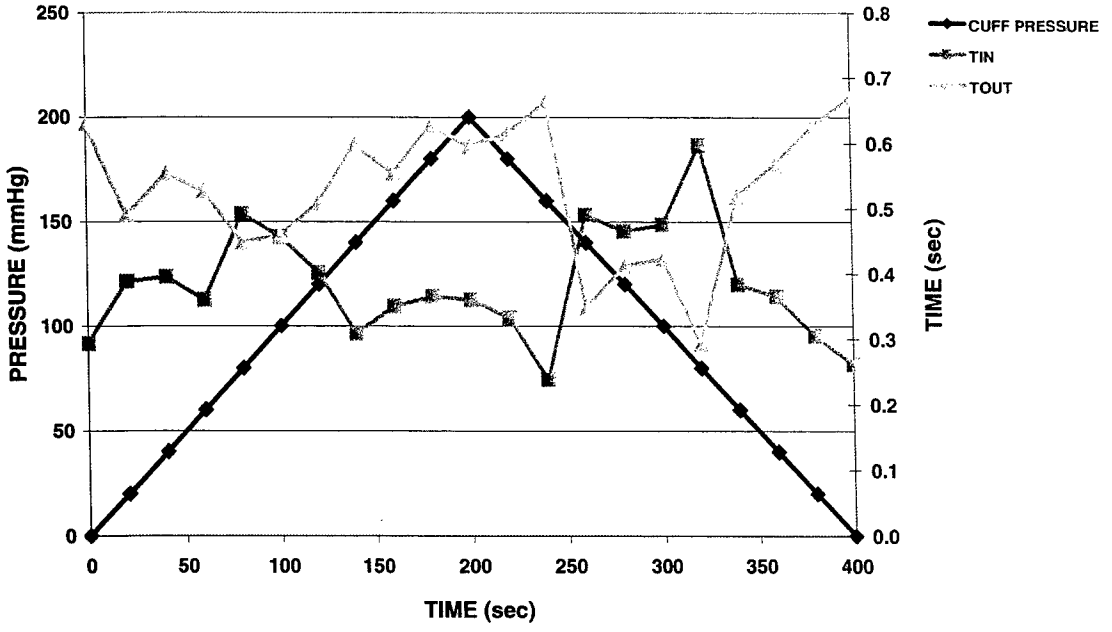

Figure F16. Cuff inflation pressure and finger blood "inflow time" (TIN) and "outflow time" (TOUT) during the blood pressure cuff test sequence.

TIN increased while TOUT decreased as the cuff was inflated to the subject's diastolic pressure. This relation reversed with further inflation of the cuff and subsequent deflation to the subject's systolic pressure. After exhibiting relatively indeterminate changes with cuff deflation from systolic to diastolic pressure, TOUT increased while TIN decreased as the cuff was brought to full deflation.

RESULTS: MAT

A second controlled forearm occlusion test was completed to investigate the possible increase in forearm blood flow accompanying application of a tourniquet. This test was conducted in a similar manner to the cuff test sequence described above except that a MAT tourniquet was used. The MAT tourniquet was arbitrarily selected; any of the other tourniquets except for the QUICK and OHT1 could have been used.

Since a tourniquet was used instead of the inflation cuff, it was impossible to record the pressure exerted upon the arm as the tourniquet was slowly tightened. During the second test a series of wrist Doppler measurements was made to assess both the velocity of blood in the monitored artery and the cross-sectional area of the vessel. These measurements visualized forearm blood flow throughout tourniquet application. The ultrasonic Doppler instrument was primarily used during this pilot test to assess whether it could be used in conjunction with a tourniquet. No attempt was made to quantify the results of the Doppler tests in this study. However, the ultrasonic Doppler images confirmed the initial increase in forearm blood flow during application of the MAT.

The results of the MAT test (Figures F17–F31) were similar to those of the cuff test sequence.

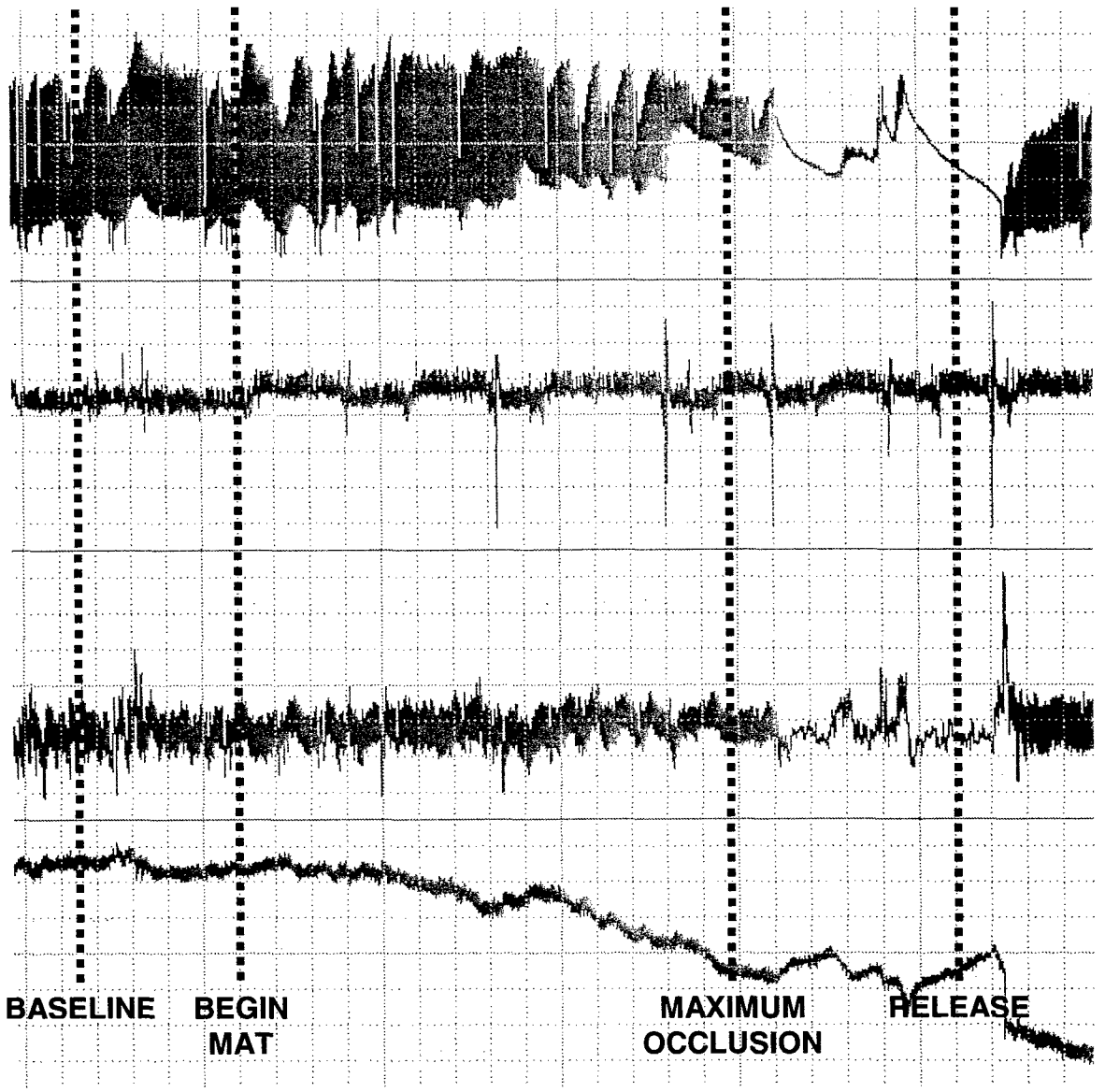

Figure F17. Compressed WinDaq A/D recording of the MAT test sequence. The four traces from top to bottom are finger blood pressure, EKG, Ro, and ΔR. No quantitative recordings of MAT occlusion pressure, analogous to the cuff inflation pressure in the cuff test, were made.

Figure F18 shows that blood flow increased during initial tightening of the MAT. Finger diastolic blood pressure tended to rise, and finger systolic blood pressure fell. At approximately 300 seconds both finger systolic blood pressure and forearm blood flow started to decrease. During the cuff inflation test, these changes occurred at the time the cuff pressure reached finger diastolic pressure.

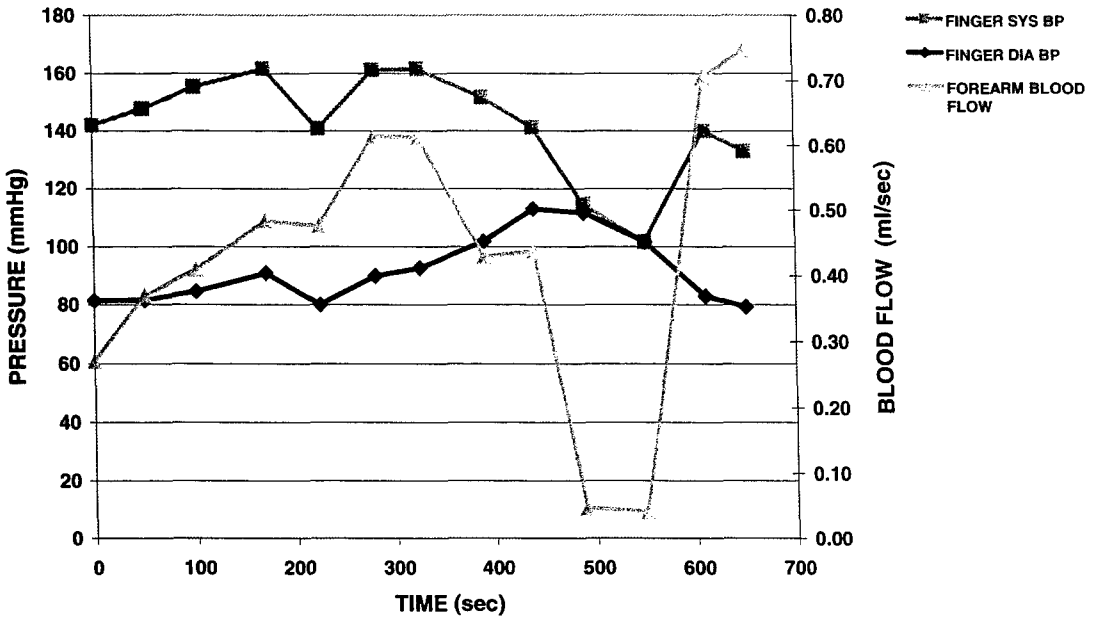

Figure F18. Finger systolic and diastolic blood pressures and forearm blood flow during the MAT test sequence.

Figure F19 shows that the finger pulse pressure remained elevated between the initial tightening of the MAT and approximately 300 sec. Pulse pressure decreased and approached zero with attainment of maximum arterial occlusion by the MAT.

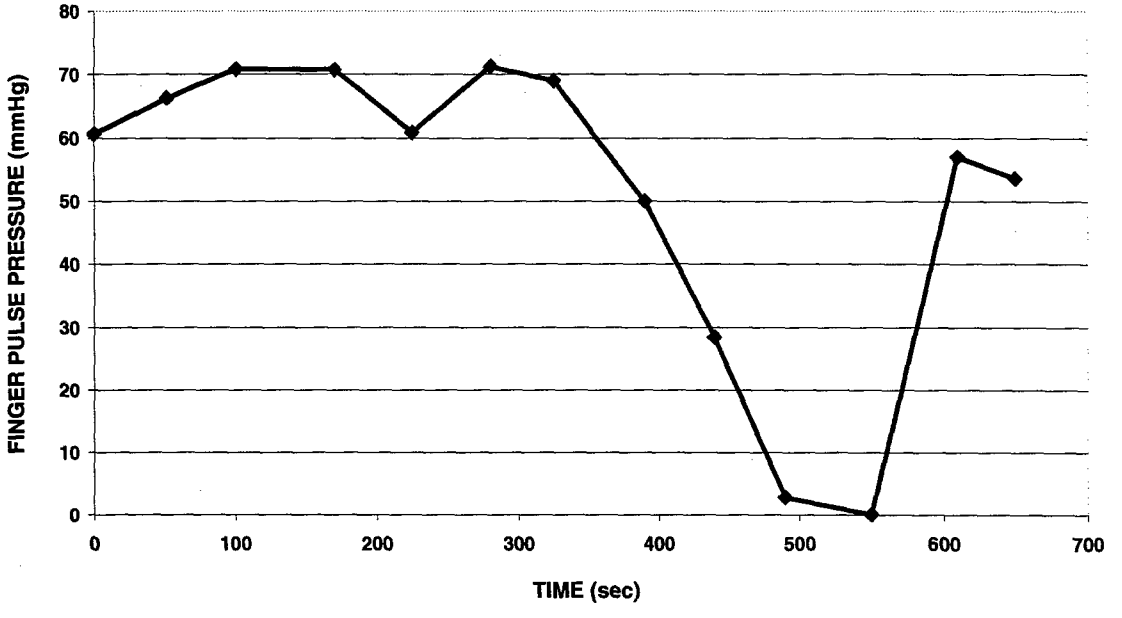

Figure F19. Finger pulse pressure during the MAT test sequence.

Figure F20 shows that the increase observed in the pulse volume with initial tightening of the MAT occurred in all pulse-specific properties: amplitude (A), total area (ST), and extrapolated height (EXHT).

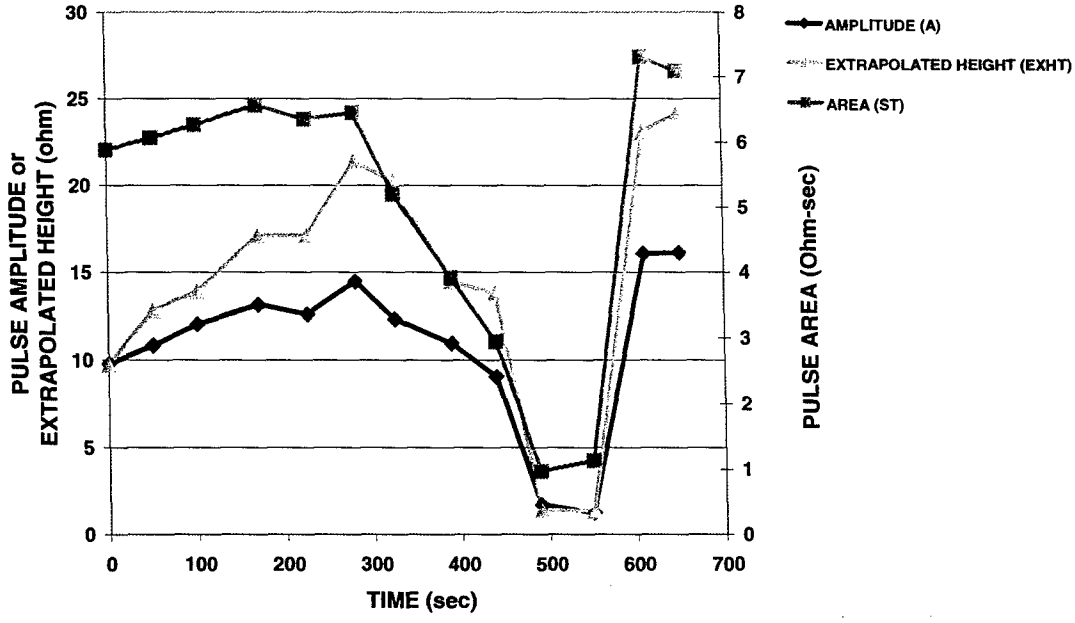

Figure F20. Impedance pulse properties during the MAT test sequence.

Figure F21 shows that the subject's heart rate increased approximately 15% during the MAT test, in contrast to the relatively constant heart rate observed during the cuff inflation test. This observation suggests that tourniquet tightening was somewhat more traumatic or stressful than inflation of the blood pressure cuff had been in that previous test.

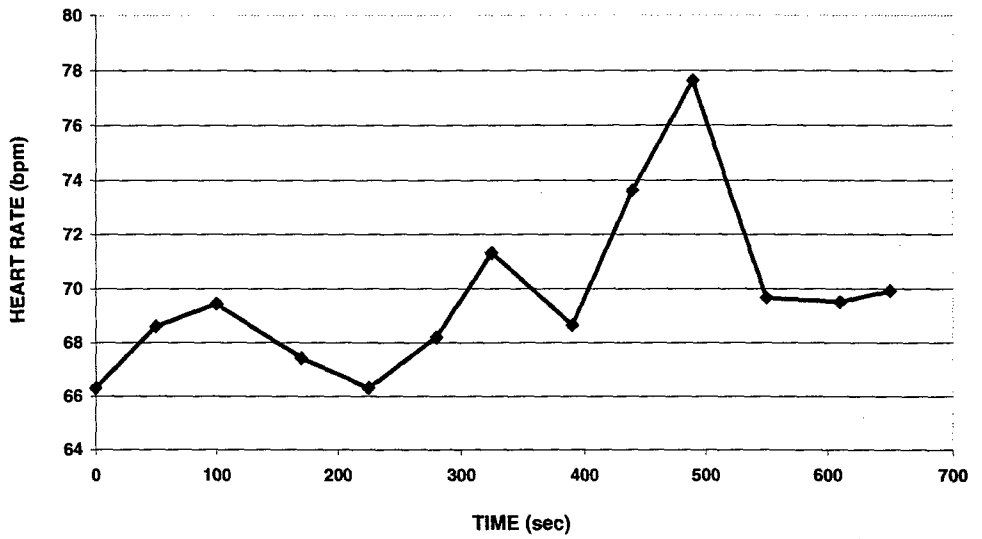

Figure F21. Heart rate during the MAT test sequence.

Finger PTT tended to increase during tightening of the MAT (Figure F22), indicating increases in vascular compliance similar to those that occurred with cuff inflation in the cuff inflation test.

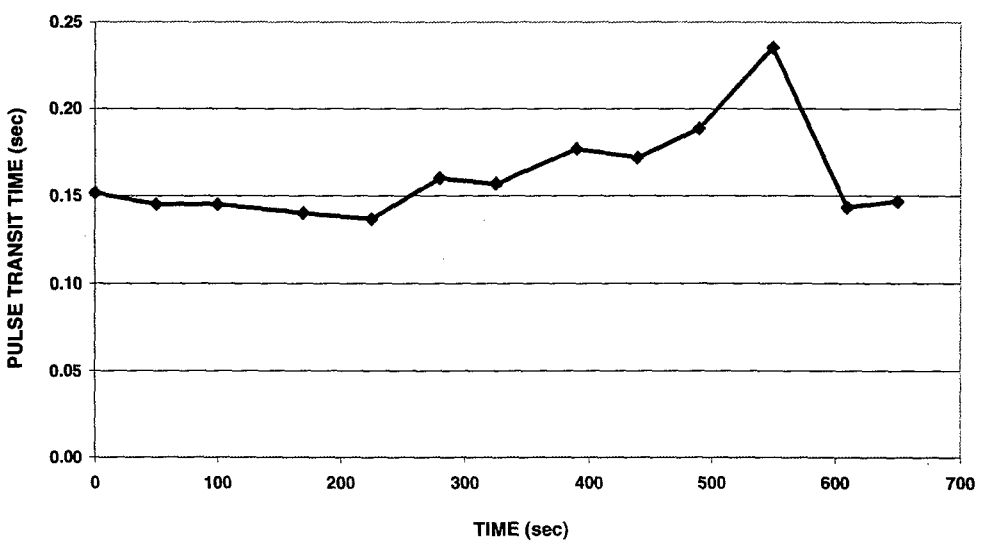

Figure F22. Finger PTT during the MAT test sequence.

Figure F23 shows that, as in the cuff inflation test, the balance of TIN and TOUT tended to change during tourniquet application, with the pattern reversing as maximum occlusion was attained.

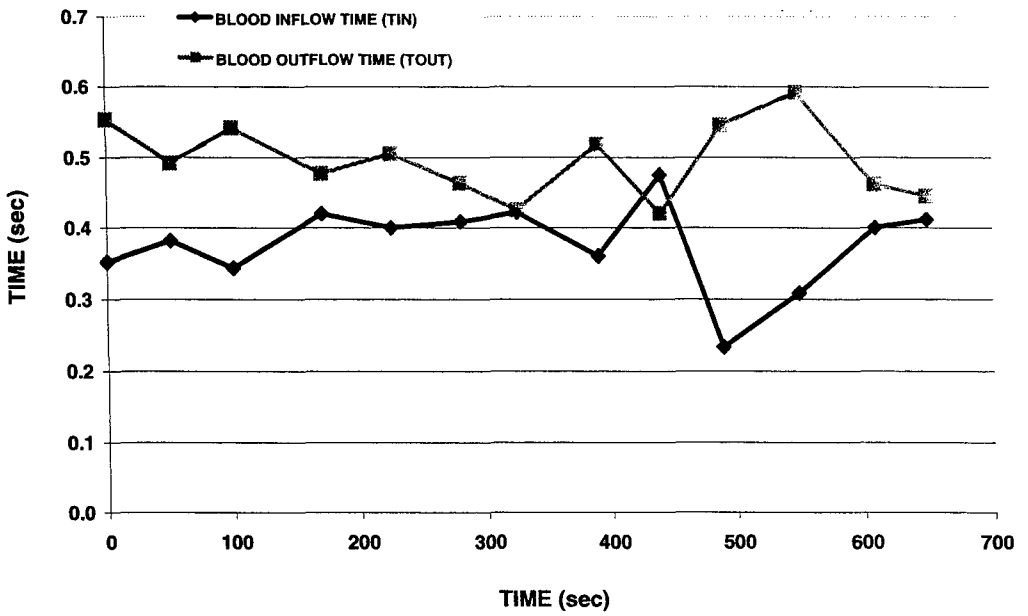

Figure F23. Finger blood flow "inflow time" (TIN) and "outflow time" (TOUT) during the MAT test sequence.

DISCUSSION

Results indicate that an increase in blood flow may indeed occur during initial inflation of a blood pressure cuff or tightening of a MAT until a pressure level equal to that of the segment's diastolic blood pressure is reached. This observation is supported by additional impedance analytical results and several measurements that may be considered independent of the impedance technique: i.e., Finapress finger blood pressures and pulse transit times.

Any extrapolation of these preliminary findings to results of the tourniquet trials would be speculative. However, it is possible that the clothing worn during these trials could have prevented the tourniquets from being tightened to supradiastolic pressures. This possibility could have been particularly true during the leg segments, where the tourniquets were found to be least effective.

It was also noted that heart rate of many tourniquet trial subjects was substantially increased as the tourniquets were tightened. This fact also increases the possibility of higher blood flows upon application of the tourniquets.

The observed increase in segmental blood flow is a potentially important finding for the design and mode of tourniquet applications on the battlefield. Further research to establish the physiologic mechanisms involved will require the presence of pressure sensors under the tested tourniquets, continuous monitoring of central and peripheral blood pressures, and additional quantitative Doppler blood flow measurements throughout each test sequence. From a practical standpoint, such research should also include studies of how tourniquet applications over different clothing ensembles affect the efficacies of the tested tourniquets.